Curtin Graduate School of Business

Green Supply Chain Management Model for the Thai Rubber Industry

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DECLARATION

To the best of my knowledge and belief, this dissertation contains no material previously published by any other except where due acknowledgment has been made. This dissertation contains no material which has been accepted for the award of any other degree or diploma in any university.

Janya Chanchaichujit

August 2014

This dissertation is dedicated to

… Dad, Anuwat Chanchaichujit, the great learner

who taught me how to learn from reading books. He bought me an encyclopaedia when I was ten. This was the most memorable gift that I have ever received.

…Mum, Armui Chanchaichujit, the great encourager

who told me to believe in the power of my dreams and never surrender. "Everything is possible" is the most encouraging advice I have ever received in my life.

Thank you to my wonderful parents for these gifts

which have become a valuable part of my life.

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In the memory of my dear father; his faith in me and my

capabilities motivates me all the time.

LIST OF PUBLICATIONS FROM THIS THESIS

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ABSTRACT

The global demand for rubber is ever-increasing. As consumption levels grow, so do the environmental problems which accompany manufacturing. Environmental responsibility is now a pressing issue worldwide, and the Thai Rubber industry is no exception. As a consequence of green measures, pressure has been put upon this industry to design a supply chain which will be environmentally friendly whilst still allowing economic gain. While current research on the Thai Rubber supply chain is available, however, none of the early works deal with issues that address economic benefits and environmental maintenance as twin, or connected concerns.

The objective of this thesis therefore, is to develop a decision-support model for the Thai Rubber industry supply chain. Specifically, the model assists in managing the Thai Rubber supply chain such that it may achieve economic gain whilst remaining environmentally friendly. In order to achieve this goal, a Green Supply Chain Management (GSCM) modelling approach was adopted. Linear-programming based single objective and multi-objective optimisation was chosen for the model development and formulation. The model was formulated by incorporating information regarding the production, distribution, and transportation of rubber products in such a manner that total costs and total GHG emissions would be minimised both separately and simultaneously. The objective of minimising the total costs represents economic performance, while the objective of minimising total GHG emissions indicates environmental performance.

The results show that by using the linear programming based single objective model, the total cost of rubber production could be improved by 1.56% relative to current industrial practice. With regard to GHG emissions minimisation, the optimal GHG emissions minimisation is 1.08 tons of GHG emissions per ton of product. An important insight gained from this model is that farmer production and manufacturing process costs

are incompatible with GHG emissions optimal results; while the results are compatible with outbound distribution transportation. However, these two objectives conflict when transport and distribution networks are restructured. In its current state, the relationship between costs and GHG emissions in the Thai Rubber supply chain, are by nature, conflicting. Consequently, a multi-objective optimisation model was developed to incorporate these two objective functions in order to capture the trade-offs between costs and GHG emissions in the supply chain network. Multi-objective optimisation along with the results of the optimisation scenario analysis concluded that a transportation restructure is more beneficial to the environment than a distribution restructure. However, from an economic perspective, restructuring distribution, along with the development of new transportation routes, appears to result in the best compromise, in that notable cost reductions may be achieved, and environmental damage is somewhat mitigated.

The contribution of this thesis were at the modelling level where GSCM modelling was captured, and at the industrial level where the Thai Rubber industry would benefit from using this model to manage the supply chain for the purpose of cost savings and GHG emissions reduction. For modelling level contribution, the single objective functions GSCM model, which was developed at the initial stage of this thesis, provided a comprehensive understanding of the basic elements of the model in relation to costs and GHG emissions. The multi-objective model provided a full set of trade-off solutions between costs and GHG emissions. From the set of alternative solutions provided, the decision maker can investigate and select the supply chain network design that most satisfies their preferences. In term of industrial level contributions, the decision-support tool can assist those in the Thai rubber industry to improve rubber production costs and decrease GHG emissions. Furthermore, supply chain network designs are able to improve policy implementation in the Thai Rubber supply chain. The establishment of rubber zoning was proposed as a way of managing the unstructured Thai Rubber supply chain. Rubber zoning can be used to support any policy related to the rubber industry. This includes: land use control for new plantations, rubber manufacturer zoning, number of traders in each region and transport infrastructure investment.

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CHAPTER 1

INTRODUCTION

Thailand is currently the world's largest natural rubber producer with a worldwide market share of 33% (OAE 2011). The Thai Rubber industry has generated a great deal of income for farmers, entrepreneurs and the economy. It is a major driver in the growth of the Thai economy with revenue generated from rubber and related-rubber product exports valued in 2011 at 22,631 million USD (TRA 2011). The Thai Rubber industry is vital to Thai society, particularly in relation to employment, with approximately six million people working in its various sectors (TRA 2007). Social welfare has also been greatly improved in Thailand, due to the rubber industry's economic contributions. The industry has been instrumental in Thailand's growing economic competitiveness in the prospective world rubber market.

Natural rubber is used to manufacture more than fifty thousand types of products (Rubberworld 2012). These range from footwear to conveyor belts to sophisticated products such as medical gloves and condoms. The majority of natural rubber is used in the automobile industry, particularly for tyres. World rubber consumption per person, per year averages 10 to 15 kilograms (German Institute of Rubber Technology 2010). This demonstrates its significance not only to the Thai economy but also to the development of the world industrial economy.

As rubber demand continues to rise, Thailand's rubber plantation areas and manufacturers have grown significantly. However, instead of strengthening industry competitiveness, preliminary research has found that the industry has not gained a competitive advantage despite the high demand for rubber. This is due to high operating costs and a lack of collaboration within the rubber supply chain (Wasusri and Chaichompoo 2008; Chanpuypetch and Kritchanchai 2009). In order to gain a competitive advantage and to remain the leader in world rubber production, research is clearly needed to support decision-making capabilities which will allow effective management and enhancement of the supply chain.

In addition to high consumption demand and the cost-competitiveness of the world rubber world market, environmental issues are becoming increasingly important in the global rubber industry. In 2008, the society of automobile industries (Korzeniewski 2008), reported that environmental issues outweighed cost savings as the industry's highest concern in 14 years. On an industry level, this concern has increased pressure on the Thai Rubber industry to find a way to embrace this challenge. The Thai Rubber Association has therefore highlighted the importance of the Thai Rubber industry being able to produce environmentally friendly products (TRA 2008). As a consequence, the need to design supply chains to achieve economic gain while being environmentally friendly has emerged as the new challenge for the Thai Rubber supply chain research paradigm.

1.1 RESEARCH BACKGROUND

1.1.1 Thai Rubber supply chain research

Research into the rubber supply chain in Thailand was initiated in 2008 in order to support strategic planning and policy, after rubber demand continued to rise. From then on, research studies were conducted by supply chain research working groups such as Wasusri and Chaichompoo (2008), Kritchanchai (2009) and Kritchanchai, Somboonwiwat and Chanpuypetch (2010). Wasusri and Chaichompoo (2008) also studied the current outbound logistic networks of rubber product exports to China. Their research found that high transportation costs were the greatest problem for the Thai Rubber industry. Other research investigating the supply chain network in the Thai Rubber industry focused on examining the inbound supply network flow (Kritchanchai 2009). The current network flow in the field was found to be the transport route with the highest costs. In addition to Wasusri and Chaichompoo (2008) and Kritchanchai (2009), Kritchanchai, Somboonwiwat and Chanpuypetch (2010) examined the supply chain of tyres for passenger cars. The research findings supported earlier works which found that an unstructured supply chain had constrained the competitiveness of the Thai Rubber industry.

Research into the literature on the rubber supply chain revealed its working state and contributed to identifying and describing the weaknesses in the chain. Early works tend to focus only on parts of the supply chain and do not adequately investigate the complete supply chain network. For instance, Wasusri and Chaichompoo (2008) studied outbound logistic networks while Kritchanchai (2009) focused on inbound logistics networks. The complete rubber supply chain including inbound, manufacturing and outbound distribution associated with total costs has not yet been studied. In addition to partially detailing the supply chain, a limited number of studies have developed decision-support models for policy makers in the Thai Rubber industry. A recent work which explored this approach is that of Chanpuypetch and Kritchanchai (2009). They created a decision-support model for route selection from Thailand to China. The Fuzzy Analytic Hierarchy Process (FAHP) was selected as a tool to create the model. However, the work appeared to develop a model framework rather than developing a decision-support model.

Sufficient works do exist which explore the weaknesses in the Thai Rubber supply chain (Wasusri and Chaichompoo 2008; Kritchanchai 2009; Kritchanchai, Somboonwiwat and Chanpuypetch 2010). Nevertheless, there is still a lack of appropriate model management tools with regard to various problems which include, in particular, economic costs and environmental impact. From a global rubber market perspective, the focus on environmental concerns puts pressure on the Thai Rubber industry to follow suit. However, none of the early works on the Thai Rubber supply chain have dealt with environmental issues or the dual issues related to the economy and the environment.

1.1.2 Green Supply Chain Management (GSCM)

A supply chain is an integrated process where business entities work together in an effort to acquire raw materials which are then converted into final products and delivered to the end customer (Beamon 1998, 281).

An important component in supply chain management design and analysis is the establishment of appropriate performance measurement tools. In model development, performance measurement is mainly considered as an objective function. The objective function based on costs, such as cost minimisation, is the most widely used objective in the literature (Beamon 1998). Other performance measurements found in the literature include customer responsiveness (Nozick and Turnquist 2001) , and customer satisfaction (Gen and Syarif 2005). In addition to the above objectives, emerging environmental concerns such as global warming have forced companies to pay more attention to environmental performance issues in their supply chain (Zhu, Sarkis and Geng 2005).

With this in mind, traditional supply chain management has expanded its scope to consider the environmental effects of all activities, from the processing of raw materials to the final disposal of goods (Srivastava 2007). The traditional notion of Supply Chain Management (SCM) has therefore been extended to become Green Supply Chain Management (GSCM), thus adding environmental criteria to decision making beyond the traditional idea of SCM (Emmett and Sood 2010). GSCM not only considers the environment in the supply chain decision-making process, but also addresses concerns about profits (Nikbakhsh 2009). GSCM has proved to be a key approach in supporting real-world decision making in different industries that must balance their economic outputs with environmental performance (Sarkis, Zhu and Lai 2011).

1.2 RESEARCH QUESTION AND SCOPE

The research questions in this thesis have emerged from the gaps in previous research into the Thai Rubber supply chain, along with the environmental concerns of the global rubber industry. The aim is to seek ways to enhance the Thai Rubber industry's competitiveness. More specifically, the overarching research question is as follows:

> *Can the Thai Rubber industry strengthen its competitiveness by reducing its total costs, while at the same time reducing its environmental impact?*

Based on the above research question, the main research objective has been developed as follows:

> *The objective of this thesis is to develop a decision-support model to allow the Thai Rubber supply chain to achieve economic gain while remaining environmentally friendly.*

The key research objectives are as follows:

- To develop a single-objective optimisation modelling framework for the Thai Rubber supply chain to minimise total costs and total greenhouse gas emissions;
- To investigate the impact of transportation and distribution restructure on costs and greenhouse gas emissions in the Thai Rubber supply chain; and
- To develop a multi-objective optimisation modelling framework for the Thai Rubber supply chain to minimise total costs and total greenhouse gas emissions simultaneously.

In order to answer the above research question and achieve the research objectives, the GSCM modelling approach was adopted, and the appropriated mathematical programming utilised, with a view to minimising total costs and total greenhouse gas emissions both separately and simultaneously. In this research, total cost represents economic performance while total greenhouse gas emissions indicate environmental performance.

The origins of GSCM can be understood based on two principles. The first principle deals with waste. The extended supply chain including reuse, recycling and remanufacturing in the reverse supply chain is the main focus of this principle (Srivastava 2007). The second principle concerns environmental issues and their relationship to external operations. The key elements in this approach are the functional areas in the forward flow that facilitate the physical movement of products along the supply chain, and the examination of how these activities can conform to environmental standards as well as improving company profitability (McKinnon 2010). As this study examines the primary and intermediate rubber products that are generally transported in bulk i.e., prior to processing and final delivery; waste and recycling processes do not form the main part of this study. It is the second principle which is of greater relevance here; that of integrating the economic and environmental criteria by incorporating the production, distribution and transportation of rubber products into the forward flow of the supply chain.

In terms of GSCM modelling design, several authors (Guillén-Gosálbez, Mele and Grossmann 2010; Wang, Lai and Shi 2011) have pointed out the necessity of incorporating uncertainties into the GSCM model. Such uncertainties in the Thai Rubber supply chain include production capacity, demand volatility, production costs, and transportation costs. The author is aware that these are important factors to take into account when developing the model. However, since this thesis is among one of the first effort to develop a GSCM model for the Thai Rubber industry, parameters which narrow and simplify volatility factors are given priority over uncertainty factors. Hence, this thesis has chosen to develop the model under the deterministic approach and as such, all parameters are assumed to be known in advance.

The model framework developed in this research therefore focuses on an investigation of the forward flow of the Thai Rubber supply chain under the deterministic approach, where all parameters are assumed to be known with relatively certainty.

1.3 CONTRIBUTION OF THE THESIS

The contributions in this research are two-fold with regard to the modelling level: how GSCM model development is captured, and how the Thai Rubber industry, at an industrial level, may benefit from using this model for cost savings and GHG emissions reduction. These contributions are expanded upon below:

Modelling level contributions:

- A GSCM modelling framework and a formula for the Thai Rubber industry to minimise total costs and total GHG emissions both separately and simultaneously.

Industrial level contributions:

- Provision of decision-support models to manage the Thai Rubber supply chain thereby improving rubber product costs and environmental performance.
- Provision of a decision-support tool to estimate the potential gain in environmental improvements compared with the costs incurred in obtaining this gain.
- Guidelines with regard to rubber zoning to assist in managing the Thai Rubber supply chain, with a view to making the Thai Rubber industry more competitive.

1.4 STRUCTURE OF THE THESIS

This thesis consists of three parts. The first part presents the background to the research in chapters 1, 2 and 3. The second part, concerning model development, is covered in chapters 4, 5 and 6. The third part, chapters 7 and 8, discusses the decision-support tools for policy implementation, and gives conclusions and recommendations for future research. An outline of the research framework is presented in Figure 1-1 below.

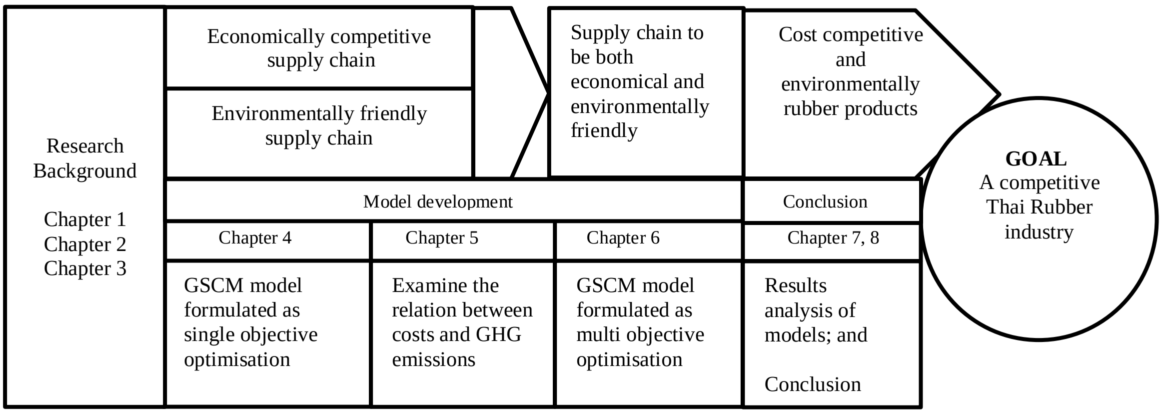

Figure 1-1: Outline of research framework

The content of each chapter is presented below:

Chapter 1: Introduction

This chapter begins with the general background related to the research. The aims of the study, research overview, research questions, research scope and structure of the thesis are then presented. The chapter concludes by outlining the contributions of the research.

Chapter 2: The Thai Rubber industry

This chapter gives an overview of the Thai Rubber industry. It aims to present the major elements of the Thai Rubber supply chain and related processes that incur costs and produce GHG emissions.

Chapter 3: Literature review

This chapter reviews previous publications and studies relating to GSCM principles, modelling and applications. It provides the theoretical background to the thesis and aims to identify any gaps in the GSCM research field.

Chapter 4: An optimisation model for the Thai Rubber supply chain

This chapter lays the groundwork for the development of the GSCM model and is a precursor to the following chapters which expand upon more complex optimisation-based modelling. Firstly, the Thai Rubber supply chain model framework is presented. Secondly, the GSCM model is formulated as single-objective optimisation. This initial stage of the model development formulates costs and GHG emissions as two single objective functions. The objective function for minimising total costs, representing economic performance while minimising total GHG emissions, indicates environmental performance. Thirdly, the optimal solution to the issues of costs and GHG emissions is depicted as an optimal network flow diagram. The chapter concludes with a discussion of the results and findings.

Chapter 5: Transportation and distribution restructure impact on costs and greenhouse gas emissions

This chapter builds on Chapter 4 by examining the relationship between costs and GHG emissions in the outbound distribution transportation network. In addition, it explores the impact of the restructuring of transportation and distribution on optimal costs and GHG emissions. The chapter ends with a summary of new insights aimed at supporting Thai Rubber industry policy makers. The chapter also aims to add to the literature regarding research into the Thai Rubber supply chain and the restructuring and design of the supply chain network.

Chapter 6: Multi-objective optimisation: Trade-offs between costs and GHG emissions minimisation

This chapter aims to address the limitations of single-objective optimisation, as developed in Chapter 4, by adopting a multi-objective optimisation model (with particular focus on a bi-objective case) for the Thai Rubber supply chain. In this chapter, the general formulation of multi-objective optimisation is reviewed. It is followed by an introduction to the ε-constraint method which calculates Pareto optimal solutions. Pareto optimal solutions to costs and GHG emissions, along with a scenario analysis are presented and discussed. The chapter concludes by detailing insights obtained from the Pareto optimal solutions.

Chapter 7: Discussion-Analysis of model results and rubber zoning guidelines

Chapter 7 discusses the results and the analyses from chapters 4, 5 and 6, with a view to policy implementation for the management of the Thai Rubber supply chain. The establishment of "rubber zoning" is then proposed, via three levels of implementation, with regard to current industrial practice, facilities, readiness and ease of implementation. This chapter aims to guide policy makers in the Thai Rubber industry as to how to investigate the possibilities of driving the private sector to initiate green awareness.

Chapter 8: Conclusions and future research

This chapter presents the conclusions of the research, along with a discussion drawn from the main findings and contributions of the thesis. The chapter closes with suggestions for future research.

1.5 SUMMARY

This chapter provides the general background related to the relevant issues in order to clarify and underline the importance of this thesis. Based on the existing literature, the chapter addresses the gap in the previous studies of supply chain in Thai Rubber industry. While the first section of the overview is devoted to identify the gap from the earlier Thai rubber supply chain research, the next section discusses how to apply the GSCM approach to fill these gaps.

The research questions, research scope and structure of the thesis are then presented. The chapter concludes by outlining the contributions of the research.

CHAPTER 2

THE THAI RUBBER INDUSTRY

2.1 INTRODUCTION

This chapter gives a general background regarding the Thai Rubber industry supply chain. It also presents the current state of the industry. The main focus of the thesis is on the rubber supply chain in Southern Thailand.

Rubber trees were first planted in Thailand in 1899. Rubber production and plantations were later promoted in the southern and eastern regions of the country, and they later spread further into the north-eastern region (See Figure 2-3). Since then, rubber plantation areas have multiplied throughout the country. In 2011, total rubber plantation areas in Thailand covered 18 million rais[1] or 2.9 million hectares (RRI 2011).

Rubber can be harvested as fresh latex. It is extracted by tapping into a long cut made in the rubber tree, and extracting the white liquid latex contents. This fresh latex can then be processed into primary rubber products such as field latex (LX), unsmoked sheet (US) and cup-lumps (CL). They are subsequently processed into different intermediate rubber products to eventually produce consumer goods. Intermediate rubber products include concentrated latex (LCT), ripped-smoked sheet (RSS) and block rubber (STR). Latex concentrate is the raw material used for dipped products such as latex examination gloves, surgical gloves, condoms, elastic threads and adhesives. Block rubber is the raw material used for high viscosity products such as shoe soles and belts. Ripped-smoked sheet rubber is used to produce vehicle tyres and industrial rubber parts (Korwuttikulrungsee 2002). Different categories of rubber products are shown below in Figure 2-1.

[1] A rai is the Thai unit used for measuring land area. One rai is equal to 1,600 square metres or 0.16 hectares

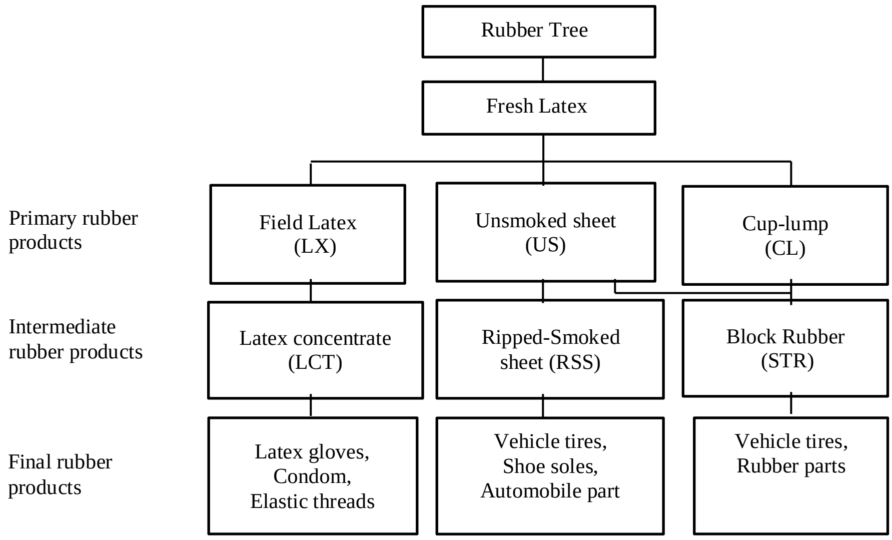

Figure 2-1: Categories of rubber products: adapted from (Jawjit, Kroeze and Rattanapan 2010)

In the following sections, a global view of the rubber industry in terms of supply, demand and price is presented. Since the Thai rubber industry is one of the largest industries in the Thai economy, economic figures are shown to illustrate how the Thai economy is driven by its rubber industry. While the first section of this chapter is devoted to an overview of the global rubber industry, the subsequent section will discuss the Thai Rubber supply chain more specifically. The Thai Rubber industry supply chain encompasses many entities and many different processes. It consists of farmers, traders, the manufacturing process, storage, distribution channels and transportation. The objective of this thesis is to develop a Green Supply Chain Management model for the Thai Rubber industry, in which minimising costs and GHG emissions are the goals. Therefore activities in the supply chain that influence costs and GHG emissions will be investigated. The chapter concludes with a summary of the key elements in the Thai Rubber supply chain.

2.2 GLOBAL VIEW OF THE RUBBER INDUSTRY

2.2.1 Natural Rubber demand

Global demand for natural rubber was 9.9 million tons in the year 2010 and it is expected to increase to 14.2 million tons by the year 2020. Demand is expected to grow at an average increase of 3.7% per annum over the next ten years, as presented in Figure 2-2 (LCM 2011).

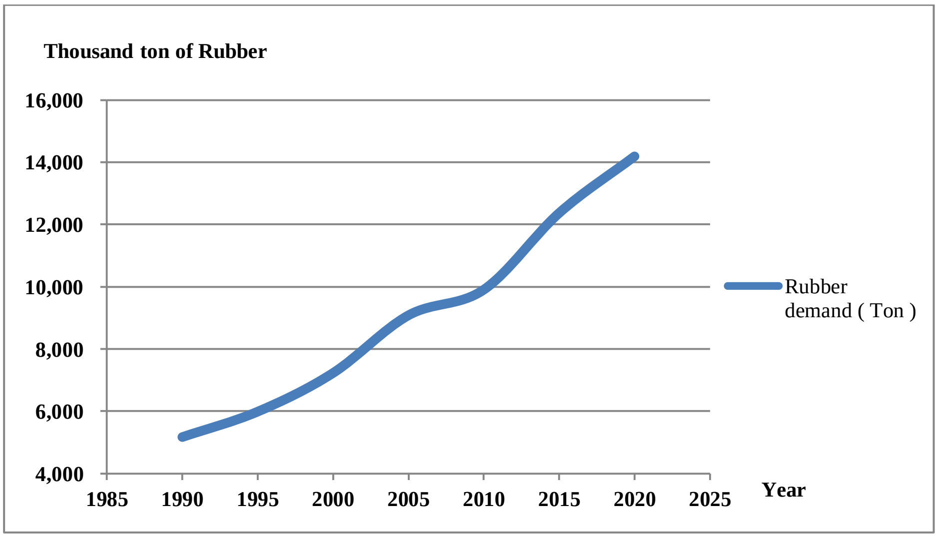

Figure 2-2: Natural Rubber demand (LCM 2011)

Strong growth in the global automobile industry is expected to drive the worldwide rubber industry with particular demand for rubber from China, India, South Korea and regions in South America (TRA 2012b). The tyre industry is the most dominant in terms of rubber consumption, accounting for approximately 70% of the total demand (LCM 2011). In addition, the rubber latex market accounts for 12% of total demand, with its main products being medical gloves. Demand from the latex market is expected to continue over the forecasting period, due to the stringency of occupational health and safety regulations and the expansion of the ageing population in the USA, Europe and Japan. Other natural rubber products include shoes soles, with non-tyre automobile components making up the remaining 18% of total demand.

2.2.2 Natural Rubber supply

Thailand is currently the world's largest natural rubber producer with a worldwide market share of 33% (see table 2-1) (OAE 2011). Indonesia, Malaysia, India and Vietnam rank from second to fifth.

Table 2-1: Global natural rubber production: unit 1,000 tons (IRSG 2011)

Country/ Year	1990	1995	2000	2005	2010	2015	2020
Thailand	1,280	1,784	2,623	2,909	3,178	3,913	3,834
Indonesia	1,270	1,467	1,501	2,218	2,411	2,805	3,141
Malaysia	1,292	1,089	928	1,126	997	1,200	1,215
India	323	500	627	772	888	1,071	1,121
Vietnam	102	159	287	443	599	904	1,261
China	264	424	480	514	672	1,034	1,146
Others	551	546	731	839	1,105	1,709	2,304
Total	5,082	5,969	7,176	8,822	9,850	12,636	14,021

The International Rubber Study Group (IRSG 2011) forecasts natural rubber production to grow at an average of 4% per annum over the years 2010 to 2020. Rubber output is expected to reach more than 14 million tonnes by the end of 2020. Thailand is expected to continue as a leading rubber producer, followed by Indonesia and Vietnam. Malaysia is forecast to lag behind Vietnam which is ranked number four in the world.

2.2.3 Price of natural rubber

A number of factors affect the price movement of natural rubber, including future market activities, currency movements, weather, and supply and demand factors (Ali, Choudhry and Lister 1997). However, the fundamental factors influencing rubber prices are supply and demand. The long-term price of rubber will depend on technological and economic developments, and in the medium-term, rubber price trends will depend on the cyclical effects of the world economy. Short-term factors such as weather, currency exchange rates and rubber trading mechanisms are the factors which will drive a rise or a fall in rubber prices. However, there are additional fundamental and speculative factors with regard to supply and demand which will have a direct effect on the rubber price at all times (AFET 2012).

2.3 THE IMPORTANCE OF THE RUBBER INDUSTRY TO THE THAI ECONOMY

The rubber industry has generated major income for farmers, entrepreneurs and the economy and it is driving the growth of the Thai economy, with revenue from natural rubber exports valued at USD 12,777 million in 2011. In addition, natural rubber and related rubber product exports overall were valued at USD 22,631 million in 2011 (TRA 2012b). The Thai Rubber industry is not only a pillar industry in the agricultural sector, but it also holds importance for Thai society, particularly in relation to employment. There are approximately one million families, or more than six million people working in this industry (TRA 2007).

The rubber industry has greatly improved social welfare in many sectors across the Thai economy. Furthermore, the rubber industry has been instrumental in the rise in the competitiveness of the Thai economy in the world market.

The economic figures presented in the previous section stress the importance of the Thai Rubber industry to the Thai economy and the development of the world industrial economy. The next section will discuss the Thai Rubber supply chain more specifically in the Southern Thailand region where the main rubber plantations and production is located.

2.4 THE SOUTHERN THAILAND RUBBER SUPPLY CHAIN

Southern Thailand is the location of the majority of Thai rubber plantations which make up fourteen province divisions: Trang, Pattalung, Satun, Songkhla, Pattani, Yala, Narathiwat, Chumporn, Ranong, Suratthani, Phangnga, Nakhon Si Thammarat, Krabi and Phuket. These fourteen provinces represent 79% of total Thai Rubber production (TRA 2010). The remaining percentages are made up of the Central region, 12%, and the North and north-eastern region, 9% (OAE 2011). For the purposes of this study, these provinces in Southern Thailand are taken to represent the Thai Rubber supply chain framework. Figure 2-3 depicts the rubber plantation areas for the whole of Thailand.

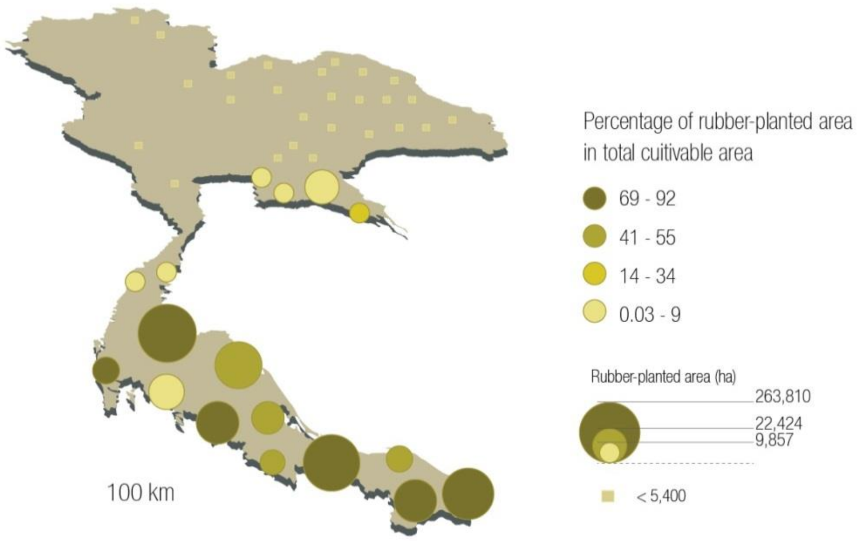

Figure 2-3: Thai Rubber plantation areas (OAE 2011)

In Southern Thailand region, the rubber supply chain starts at the farm level where rubber farmers produce fresh latex before processing it into primary rubber products. These include field latex, unsmoked sheets, and cup-lumps. The products are sold through established local market traders in villages, or in sub-provincial cities in each province. There are three trader groups in Thailand: the general market, the cooperative and the dealer. Market traders deliver the primary products down the chain to the factories, with each factory in each province processing the intermediate rubber products before delivering them to the domestic customer or export outlet. Some of the products may be kept as domestic stock.

Figure 2-4 below illustrates the schematic framework for the Thai Rubber supply chain.

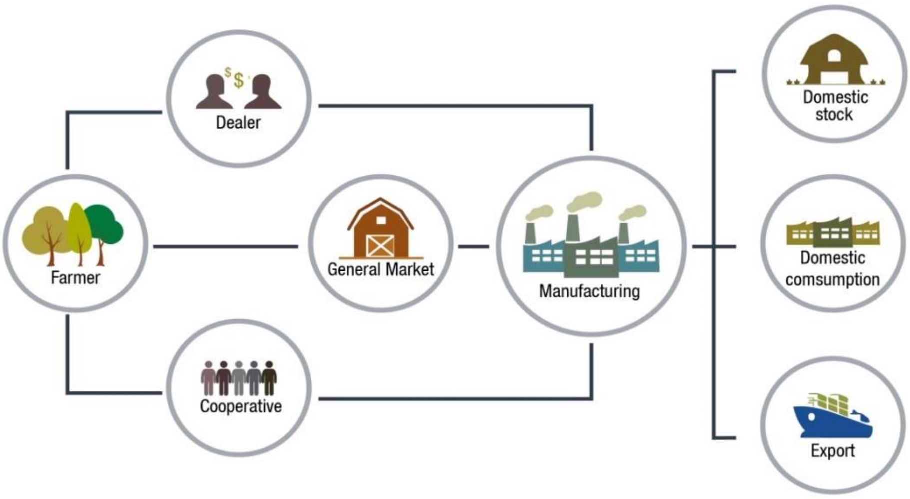

Figure 2-4: The schematic framework for the Thai Rubber supply chain (Developed for this research by the author)

In the next section, the common definition for each rubber entity and its relevant process is explained.

2.4.1 Farmer

Kaiyoorawong and Yangdee (2006) have defined the rubber farmer as:

- Someone with land rights to plant rubber trees on State land;
- Someone who uses their own labour, or that of waged workers to grow, manage and tap rubber trees. Or;

- Someone who is a producer of rubber latex and sheets but who is not involved in high technology rubber processing or export processing.

The farmers' rubber group is classified according to the plantation area each farmer occupies. There are three sizes of Thai Rubber farm; small, medium and large with land being 25,100 and 500 rais of land occupation (ORRAF 2012). In 2011, there were approximately one million rubber farmer families or more than six million people (TRA 2007) producing rubber in the form of field latex, unsmoked sheets and cup-lumps.

2.4.2 Trader group

At the local market trading level, trader groups collect and buy primary rubber products from rubber farmers and then sell it down the chain to the manufacturer to process into intermediate rubber products. There are three groups of rubber traders in Thailand: the dealer (DL), the cooperative (CO) and the general market trader group (GM) which account for 80%, 10% and 10% of total rubber trading volume respectively. The major local trader group in Thailand consists of local dealers. According to the Thai Rubber Research Institute (2011), there were 1,822 registered dealers in Thailand. The rubber cooperative is another dominant trader group established in Thailand by the government. The aim of the cooperative is to support rubber farmers at the community level in terms of funding, and knowledge and techniques related to plantations and local markets. The cooperative members also benefit from economy-of-scale when they are selling rubber products to dealers. There were 700 rubber cooperatives throughout Thailand in 2011 (ORRAF 2012). The general market trader group is also called the central rubber market in Thailand. The general rubber market was established as a rubber auction market. Currently, there are three general markets in Southern Thailand. These are located in the Songkhla, Suratthani and Nakhon Si Thammarat provinces.

2.4.3 Manufacturing

The manufacturers process the primary rubber products into intermediate rubber products. There are three types of intermediate rubber manufacturing processes as follows:

Ripped-smoked sheet (RSS) process:

Ripped-smoked sheet is rubber sheet which has undergone the smoking process at a controlled temperature before being classified according to level of quality. The products are then generally packed into bales for storage or shipment. Ripped-smoked sheet is used as raw material in the manufacture of products such as tyres, shoe soles and automobile parts. Figure 2-5 illustrates the ripped-smoked sheet production process.

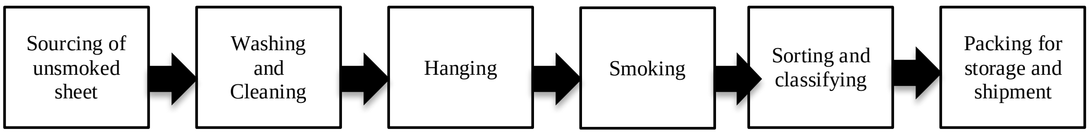

Figure 2-5: The ripped-smoked sheet production process (STA 2012b)

Block Rubber (STR) process:

Block rubber is produced from a mixture of cup-lumps and unsmoked rubber sheet. In the block rubber production process, the raw materials are cut and washed before being flattened into a crepe shape. The material then goes through the dryer process to remove excess water and is then compressed into a block shape for storage or shipment. Block rubber is the raw material used in the production of tyres for automobiles and aeroplanes. The block rubber production processes are showed in Figure 2-6.

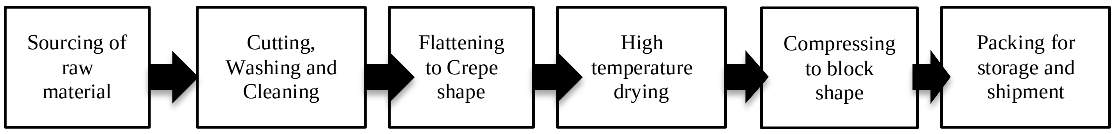

Figure 2-6: The Block rubber production process (STA 2012b)

Latex Concentrate (LCT) process:

Latex concentrate is derived from field latex in liquid form. In the latex concentration process, the raw materials are centrifuged to separate out the impurities. Ammonia is then added to prevent coagulation before packing for storage or shipment. Concentrated latex is used primarily in the manufacture of various products such as latex examination gloves, surgical gloves, condoms, elastic threads and adhesives. Figure 2-7 shows the latex concentration production process.

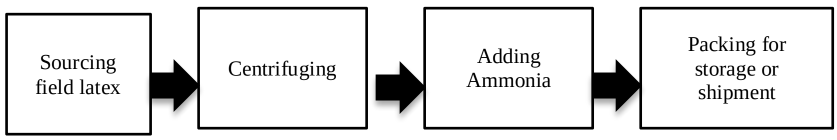

Figure 2-7: The Latex concentrate production process (STA 2012b)

2.4.4 Storage

Natural rubber is considered to be an important cash crop in Thailand. The lead-time from rubber farmer to trader is relatively short; occurring on a daily basis. Therefore, storage is not an issue at the inbound supply level. At the manufacturing and exporting tier, stock levels of intermediate rubber products are more important in determining the selling price and overcoming shortages during the winter season. During winter, the supply may fall to as low as 20% of regular production output. The relationship between supply and demand with regard to rubber products may lead to a rise or fall in price. However, storage levels at the manufacturing tier have only been investigated with regard to rubber price speculation rather than with regard to logistic planning strategies. In addition, the storage levels of rubber products for each manufacturer are treated as confidential. Thus, in this thesis, storage and related factors such as location, levels and costs are not included in the analysis.

2.4.5 Distribution channels

There are three main outbound distribution channels for rubber products in Thailand; domestic stock, domestic consumption and export.

Domestic stock:

The domestic stock of rubber products is managed by the government in terms of a regular intervention program to manage supplies. It was established to administrate and shore-up rubber prices to safeguard against price-dropping. Domestic stock generally plays a price-support role in the Thai rubber industry, with stock levels averaging 10% of total annual production. There is an obligation to sell rubber stock products at the appropriate time to the Rubber Estate Organisation (REO), the only agents authorised under government contract to export rubber stocks to international markets.

Domestic consumption:

Domestic consumption of rubber products in Thailand is approximately 15% of total annual production (TRA 2010). These primary rubber products mainly go to the rubber processing industries for the manufacture of such items as automobile tyres, gloves, condoms, rubber bands and rubber elastic.

Export:

Approximately 75% of the rubber produced in Thailand in 2011 was exported, mostly in the form of block rubber, ripped-smoked sheet and latex concentrate (TRA 2011). The major importers of Thai rubber products are China, followed by the USA and Japan (TRA 2012b). Exports therefore make up the largest proportion of Thai Rubber production.

2.4.6 Transportation

Transportation from farmer group to trader group, and from each trader group to the factory is mainly undertaken by road, as travel-distances are relatively short at the provincial level. Farmers generally use four-wheel or ten-wheel trucks, depending on the amount of rubber product transported. Transport from the rubber plantation to the trader is the responsibility of the farmer. From trader group to factory, the ten-wheel truck is used and is the responsibility of either trader or manufacturer, depending on the trading contract. Outbound distribution from manufacturer to destination comprises different combinations of freight modes such as road, rail and sea. This area is the responsibility of the rubber manufacturer.

The total transportation costs for the Thai Rubber supply chain can be divided up into 3% for the farmer to trader group and 5% for the trader group to the manufacturer. Another 92% of transportation costs come from the outbound distribution transport from manufacturer to domestic customer, domestic stock location or exporting ports (OAE 2011). It is important to note that the largest portion of transportation costs come from outbound distribution. Thus, further analysis of transportation activities and costs in this section and the chapter that follows will focus more specifically on outbound distribution transportation. There are fourteen routes in the outbound distribution network, as shown in Figure 2-8.

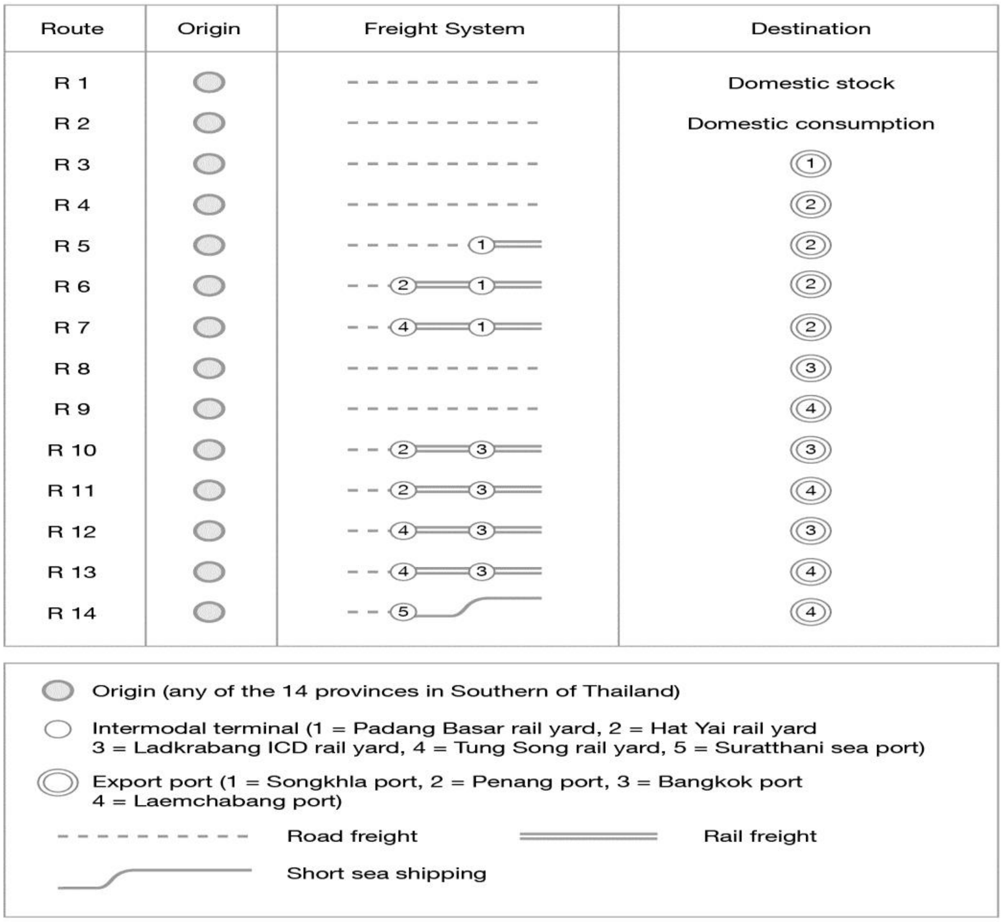

Figure 2-8: The fourteen routes in the outbound distribution network

In Southern Thailand, the main hubs for rubber activities and export gateways are the Songkhla, Suratthani and Nakhon Si Thammarat provinces. These three provinces have intermodal terminals which handle regional cargoes, serving major export ports in Thailand and Malaysia (Songkhla port, Bangkok port and Laemchabang port in Thailand, Penang port in Malaysia). The Songkhla province which is located in the lower south has Hatyai and Padang Basar rail yards as intermodal terminals which then eventually make connections with the port of Songkhla in Thailand and Penang port in Malaysia. Nakhon Si Thammarat province is located in the upper south with the Tung Song rail yard intermodal terminal which connects to Bangkok port and Laemchabang port. The Suratthani coastal line seaport is the only short-sea shipping seaport terminal which has access to Laemchabang port.

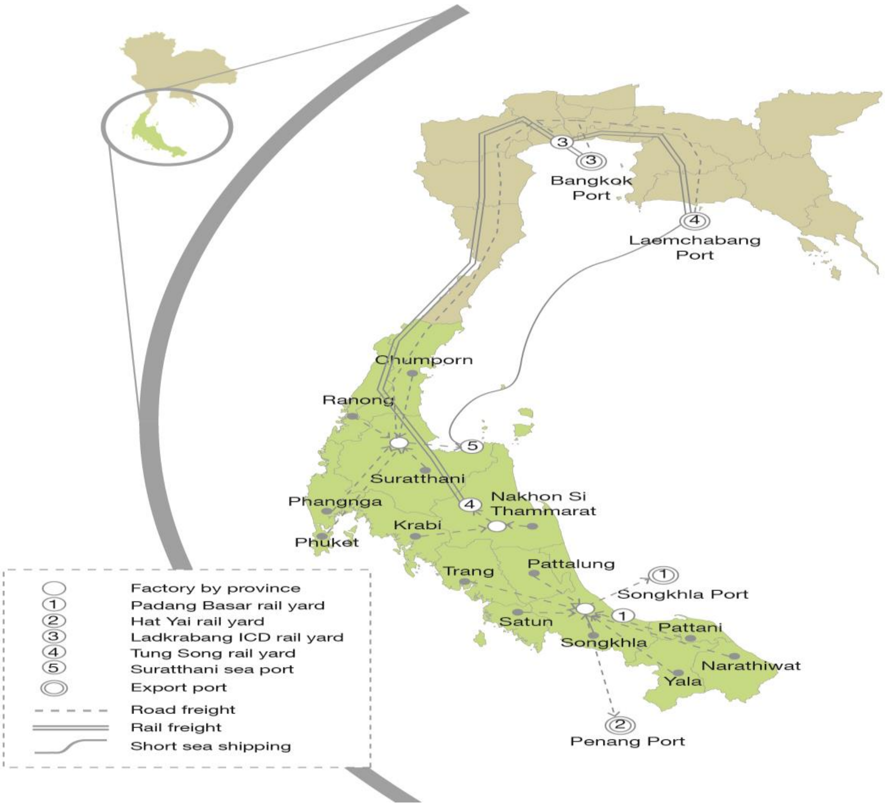

Figure 2-9: The outbound distribution transportation network

Figure 2-9 depicts the transportation network of the Thai Rubber supply chain outbound distribution network. Routes R1, R2, R3, R4, R8 and R9 are the direct transport routes taken by truck. The routes originate from many provinces in the Southern region, with products being destined for domestic stock, domestic consumption, Songkhla port, Penang port, Bangkok port and Laemchabang port.

Route R5 is a combination of road and rail transport. Trucks are used to transport cargo from its point of origin to the Padang Basar rail yard intermodal terminal and rail is then used to transport the cargo to Penang port in Malaysia. Routes R6, R7, R10, R11, R12 and R13 use a combination of road and rail transport. For these routes, cargo is transported by truck from point of origin to the first intermodal terminal, then by rail from the first intermodal terminal to the second intermodal terminal, and finally by rail to port. For routes R6 and R7, cargo is transported by truck from point of origin to Hatyai train station and Tung

Song train station, and then from these stations to Padang Basar train station and on to Penang port in Malaysia. For routes R10 and R12, cargo is transported from Hatyai and Tung Song rail yard intermodal terminals and Ladkrabang rail yard intermodal terminals to Bangkok port. Cargo for routes R11 and R13 is transported to Laemchabang port. Route R14 is a combination of road and sea. Cargo is transported by truck from point of origin to the Suratthani coastal line seaport terminal. The cargo is then moved by sea to Laemchabang port.

2.5 COSTS AND GREENHOUSE GAS EMISSIONS FROM THE THAI RUBBER SUPPLY CHAIN

The objective of this thesis is to develop a GSCM model for the Thai Rubber industry which will minimise total costs and total GHG emissions simultaneously. Therefore, it is clear that costs and GHG emissions must be the main parameters in model development. In this section, findings on costs and GHG emissions in the Thai Rubber supply chain are presented.

2.5.1 Costs of the Thai Rubber supply chain

The total costs of the Thai Rubber supply chain are expressed as a summation of two components; rubber processing costs and transportation costs. As mentioned earlier in Chapter 1 that this thesis has chosen to develop the model under the deterministic approach and as such, all costs are assumed to be fixed costs.

The rubber processing cost component includes the cost of: primary rubber production, trading rubber, intermediate rubber production and the export of intermediate rubber products. The costs of primary rubber production include the costs of establishing and maintaining plantations, along with labour costs which also represent the major costs of trading rubber and exporting intermediate rubber products. Raw material, equipment, electricity and labour are some of the costs associated with intermediate rubber production, with major costs consisting of raw material and labour, which represent 26% and 34% respectively. The rubber processing costs component makes up 60% of the total costs of the Thai Rubber supply chain (Kunarasiri and Srivarin 2007)

Transport costs include the costs of transportation for the various rubber entities along the supply chain. Transport costs depend on mode, type of vehicle used and distance travelled. They include the cost of transport from: farmer to trader group to factory, to gateway node to freight route to destination. It is noted that transportation costs from factory to gateway node en route to destination have been defined as outbound distribution transportation in the previous section. Transportation costs throughout the rubber supply chain make up 40% of the total costs.

As mentioned previously, storage is not a significant factor in the analysis of the Thai Rubber industry. Therefore this thesis will not take into account any costs related to storage.

The cost structure for the Thai Rubber supply chain is depicted in the framework in Figure 2-10.

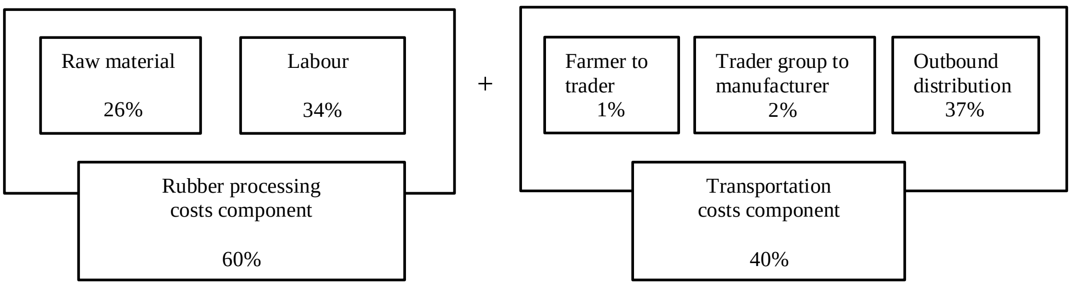

Figure 2-10: Cost structure of the Thai Rubber supply chain (Kunarasiri and Srivarin 2007)

It is important to note that this cost-structure ratio was calculated based on ripped-smoke sheet production. Therefore the cost structure for other products such as latex concentrate and block rubber may have some variations from the diagram below. However, this cost structure has been verified as representing the cost structure of the Thai Rubber supply chain (OAE 2012).

2.5.2 GHG emissions from the Thai Rubber supply chain

GHG emissions from the Thai Rubber supply chain occur at various stages, from the rubber plantation right through to the production of intermediate rubber finished products and transportation through the supply chain.

The rubber processing GHG emissions component comprises two activities: those in the rubber plantation and those of production. Jawjit, Kroeze and Rattanapan (2010) quantified emissions of GHGs associated with the production of fresh latex and three intermediate rubber products including latex concentrate, ripped-smoke sheet and block rubber. In the study by Jawjit, Kroeze and Rattanapan (2010), GHG emissions were estimated by following the IPCC 2006 guidelines for national greenhouse gas inventories (IPCC 2006). The emissions of CO_2 (CH_4, N_2O) were calculated in kilograms per ton of rubber product, and then converted to the equivalent quantity of carbon dioxide (CO_2-eq) using Global Warming Potential (GWP) measures. Greenhouse gas emissions were calculated for fresh latex and primary rubber products at the plantation stage, followed by emissions calculations for the intermediate rubber production stage. Finally, the overall GHG emissions were combined as a summation of GHG emissions from both stages, and presented in terms of intermediate rubber product GHG emissions. The unit is expressed as tons of CO_2-eq per ton product. Table 2-2 summarises rubber product GHG emissions from rubber produced from land-converted plantations and original rubber plantation areas.

Table 2-2: Rubber product GHG emissions (Jawjit, Kroeze and Rattanapan 2010)

Intermediate rubber product	Case1: Rubber produced from land converted plantations (Eastern, North and North-eastern region rubber plantation) Unit : ton CO_2-eq / ton product	Case2: Rubber produced from original rubber plantation area (Southern region rubber plantation) Unit : ton CO_2-eq / ton product
Latex concentration (LCT)	13	0.54
Ripped-smoke sheet (RSS)	21	0.66
Block rubber (STR)	13	0.70

For transportation along the rubber supply chain, the level and type of GHG emissions depends on the mode of transport, payload and distance travelled. The greenhouse gas emissions calculation for transportation across each route is calculated by using an activity-based approach. Transportation in the rubber industry is generally operated by a third party freight forwarding company. Therefore, the activity-based approach is seen as an appropriate method for this industry.

The formulation used for the activity based method (DEFRA 2004) is as follows:

Greenhouse gas emissions (ton) = weight of goods[2] (ton) $\times$ total distance travelled[3] (kilometre) $\times$ GHG conversion factor[4] (ton CO_2–eq. / ton kilometre) (1)

The GHG conversion factor for the transport used in this thesis was adopted from the Thai National Life Cycle Inventory (Thai LCI) database (TGO 2012a). Table 2-3 below presents the GHG conversion factors for each transportation mode.

[2] The standard weight of goods for rubber product in Thailand is 25 Tons.
[3] See Table A-16 in Appendix for total distance travelled in each province.
[4] See Table 2-3 for each transportation mode GHG conversion factor.

Table 2-3: GHG conversion factors for each transportation mode

Transportation mode	GHG conversion factors kilograms CO_2-eq / ton kilometre	Data Source
Truck 4 wheels, 7 tons full by weight - 0% loading - 50% loading - 75% loading - 100% loading	 0.3105 0.2676 0.1825 0.1399	Thai LCI database (TGO 2012b)
Truck 10 wheels, 16 tons full by weight - 0% loading - 50% loading - 75% loading - 100% loading	 0.5851 0.0964 0.0685 0.0529	Thai LCI database (TGO 2012b)
Truck 18 wheels, 32 tons full by weight - 0% loading - 50% loading - 75% loading - 100% loading	 0.8629 0.0798 0.0525 0.0408	Thai LCI database (TGO 2012b)
Short sea shipping (container shipment)	0.0446	Thai LCI database (Ecoinvent 2.2, IPCC2007 GWP100a) (TGO 2012b)
Rail transportation	0.01111	Thai LCI database (Ecoinvent 2.2, IPCC2007 GWP100a) (TGO 2012b)

The GHG conversion factor for road freight transport was developed based on a composite of the fleet and loading factor in Thailand. The different load factors are specified by the level of loading at 0%, 25%, 75% and 100% full by weight. For other modes of transport (rail and short-sea shipping) GHG conversion factors, the Thai LCI database was taken from the Ecoinvent database version 2.2.

Figure 2-11 illustrates the total GHG emissions calculation framework for the Thai Rubber supply chain.

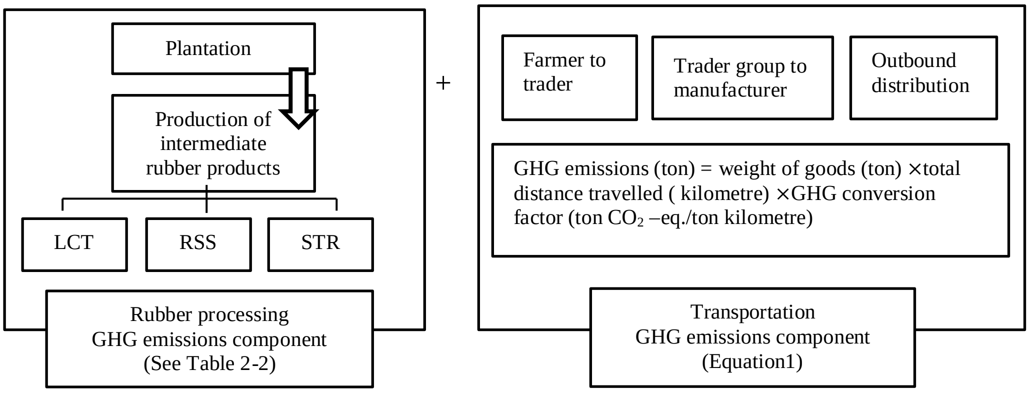

Figure 2-11: GHG emissions calculation framework for the Thai Rubber supply chain (Developed for this research by the author)

The total GHG emissions are composed of rubber processing GHG emissions component and transportation GHG emissions component. As Southern Thailand region rubber plantation is planted on the original rubber plantation area, the GHG emissions by products are 0.54, 0.66 and 0.70 ton CO_2-eq / ton of product for LCT, RSS and STR respectively (See Table 2-2). For transportation GHG emissions component, it can be calculated as described in equation 1 in section 2.5.2. Finally, the overall GHG emissions of the Thai Rubber supply chain were combined as the summation of these two components.

2.6 SUMMARY

This chapter has set the context of the thesis by introducing an overview of the Thai Rubber industry as well as the major elements in the Thai Rubber supply chain. The economic figures presented in this chapter stress the importance of the Thai Rubber industry to the Thai economy and to the development of the world industrial economy.

It has been observed that the Thai Rubber supply chain involves a million rubber farmers at farm level through to a thousand trading groups and a hundred manufacturing processors of rubber products. Therefore, a decision-support model that promotes a more efficient Thai Rubber supply chain is clearly needed. To be competitive in the world rubber market, environmental criteria must be monitored, along with traditional economic performance, i.e., costs. As such, Thai rubber policy makers should carefully address these two performance measures in a comprehensive manner in order to remain the leader in the prospective rubber world market.

In the next chapter, previous publications and studies related to GSCM principles decision-support modelling and applications will be reviewed. It aims to provide the theoretical background to the thesis and aims to identify any gaps in the GSCM research field for the research into the Thai Rubber supply chain.

CHAPTER 3

LITERATURE REVIEW

3.1 INTRODUCTION

This chapter presents an overview of the literature on Green Supply Chain Management (GSCM). It includes several aspects of the modelling and mathematical approaches in GSCM which are relevant to the thesis and it indicates how the thesis contributes to the existing literature. Firstly, a brief overview of supply chain model design and GSCM principles and terminology are presented. The modelling approaches in GSCM are then discussed. This section focuses on the modelling approaches in the literature in terms of their theoretical aspects and application to real-world problems. The eventual aim is to propose an integrated modelling approach for the Thai Rubber industry GSCM model. Particular attention is paid to the mathematical method of optimisation-based modelling and appropriate solutions for the rubber industry.

3.2 SUPPLY CHAIN MANAGEMENT (SCM)

A supply 'chain' is an integrated process wherein a number of various business entities work together in an effort to acquire raw materials which are then converted into final products and delivered to the customer (Beamon 1998, 281). The complexity of the supply chain may vary from industry to industry and from business to business. Beamon (1998), classified a supply chain into two integrated processes: (1) the production planning and inventory control process, and (2) the distribution and logistics process. When designing a supply chain network, four main decision areas within these two integrated processes must be considered: (1) location, (2) production, (3) inventory, and (4) distribution and transportation. In these decision areas, there are three levels involved: strategic, technical and operational. Strategic decisions are made over a longer timeline to dictate the supply chain configuration (Sarkis 2003).This includes the selection of production, storage and distribution locations (Huang, Lau and Mak 2003) and the capacities of warehouses, or the flow of material through the logistics network (Melo, Nickel and Saldanha-da-Gama 2009). Technical decisions involve several activities, such as the selection of suppliers, production, inventory and types of transportation mode (Lambert and Cooper 2000). Finally, operational decisions which consider the day-to-day flows of products in the supply chain, such as scheduling and routing activities (Gunasekaran, Patel and McGaughey 2004) are undertaken. An extensive review of strategic, technical and operational decision making models can be found in Cooper , Lambert and Janus (1997).

Another important component in supply chain management, in addition to model design and analysis in each decision area, is appropriate performance measurement. In the supply chain model design, performance measurement is mainly considered as an objective function. The most widely used objective function in the literature is based on financial elements, such as cost minimisation and profit maximisation. In the supply chain performance measurement review of Melo, Nickel and Saldanha-da-Gama (2009), financial performance and cost and profit represents 91%, while other performance measure results were only 9%. However, Melo, Nickel and Saldanha-da-Gama (2009) observed that cost minimisation has received more attention from researchers than has profit maximisation. Examples of cost minimisation research can be found in the work of Berman and Wang (2006). They investigated a strategy for distribution and transportation for inbound logistics planning in which inventory and transportation costs are minimised. The author mentioned that these two cost components are a significant financial factor in the supply chain.

Other important performance measurements in the literature, in addition to cost minimisation, are customer responsiveness (Nozick and Turnquist 2001), and customer satisfaction (Gen and Syarif 2005). The work of Nozick and Turnquist (2001) deals with costs and customer responsiveness in the supply chain network design. The authors developed a model to optimise distribution centre locations that trade-off total costs against service responsiveness. In this particular study, the concept of "service-cost trade-offs" was introduced. The research concluded that the nearer the distribution centre locations to the final customer, the lower the costs and the higher the customer responsiveness. However, Handfield and Bechtel (2002) presented a different view of customer responsiveness performance. In their work, they concluded that the roles of trust and relationship structure management are two factors that could improve customer responsiveness in the supply chain.

In terms of costs and customer satisfaction, Gen and Syarif (2005) proposed measuring the accuracy of delivery of products as customer satisfaction performance. In this study, an optimisation model was developed to determine the production quantity of each product, each plant and each inventory strategy to satisfy the resource capacity and customer demand with minimum costs while maximising customer satisfaction. In addition to delivery products accuracy, Li et al. (2006) defined customer complaints management as another tool to improve customer satisfaction. In addition to customer responsiveness and customer satisfaction, quality is another important performance measure mentioned in the literature. Danalakshmi et al. (2012) introduce the concept of quality cost-related programs under quality-related concepts. Wu and Olsen (2008) took a further step in investigating three supply chain performance measures: cost, quality and on-time delivery for supplier selection.

It is noteworthy that the work on supply chain model design is greatly influenced by decisions made from a financial perspective. While there have been some attempts to work on dimensions such as customer satisfaction, customer responsiveness, quality and on-time delivery, early supply chain models made no financial provisions for the integration of environmental objectives. Therefore, performance measurements should be expanded to address growing environmental concerns.

3.3 GREEN SUPPLY CHAIN MANAGEMENT (GSCM)

Environmental pollution and waste is generated at all stages in the supply chain, from resource extraction to manufacturing, distribution and use of goods (Srivastava 2007, 54). Emerging environmental concerns such as global warming have now forced companies to pay more attention to environmental issues in the supply chain. Early work on supply chain management paid little attention to environmental pollution and waste produced from the supply chain, nor did it adequately address environmental concerns in supply chain modelling. A fundamental shift in these traditional management techniques is required such that environmental issues are appropriately integrated.

When traditional Supply Chain Management (SCM) principles take into account the environmental aspects of all activities, from raw materials to the final disposal of goods, the notion may then be widely extended to Green Supply Chain Management (GSCM). In other words, GSCM adds environmental criteria to decision-making beyond traditional supply chain management (Emmett and Sood 2010). Grossmann and Guillen-Gosalbez (2010) define GSCM as the combining of environmental management and supply chain management into a single framework. In addition, GSCM is not only concerned with the environment in the supply chain decision-making process but also with financial profits (Nikbakhsh 2009).

The origin of GSCM is based on two principles. The first principle deals with waste-directed and emissions-directed technology, such as the reuse of materials or the recovery of products. The aim behind the principle is to analyse problematic environmental issues that occur throughout the life-cycle of the product as it travels through the entire supply chain (Bloemhof-Ruwaard et al. 1995). Research regarding this principle is prolific (Sheu, Chou and Hu 2005; Jayaraman 2006; Sheu 2008; Quariguasi Frota Neto et al. 2008; Quariguasi Frota Neto et al. 2009; Gupta and Evans 2009). One common finding mentioned from the above authors is that consumers and government are the major drivers in forcing companies to mitigate the environmental impact of the supply chain. European legislation, as an example from a government point of view, has forced companies to environmentally manage used products and waste (Quariguasi Frota Neto et al. 2008; Quariguasi Frota Neto et al. 2009) Furthermore, global enterprises such as IBM, Hewlett-Packard and Xerox have made an effort to green their supply chain by implementing green measurements in assessing their suppliers (Sheu, Chou and Hu 2005). As a result, this GSCM principle has gained increasing attention not only from academia but also from the private and public sectors (Sarkis, Zhu and Lai 2011).

The second principle is concerned with environmental problems as they apply to the internal operations that interface with external organisations; the purpose being to ensure that the products and services meet with environmental standards (McKinnon 2010). McKinnon (2010, 16) has pointed out that this GSCM principle has become the major concept in recent GSCM development areas such as green design, green purchasing, eco-efficiency, environmental management systems, and sustainable supply chain. The work related to this principle includes that of (Rao 2004; Chen 2005; Linton, Klassen and Jayaraman 2007; Zhu, Sarkis and Lai 2008). In this principle, Rao (2004) and Chen (2005) highlighted that the greening of internal operations is a key activity in managing the Green Supply Chain. Rao's work (2004) focused on green purchasing while Chen (2005) concentrated on green production. Linton, Klassan and Jayaraman (2007) proposed a broader adoption of GSCM to include product design, the manufacturing of by-products and by-product from product use. In terms of benefits obtained from the implementation of this GSCM principle, Zhu, Sarkis and Lai (2008) emphasised that GSCM has emerged as an important management tool. It allows organisations to achieve corporate profits whilst at the same time reducing environmental risks.

The progress in GSCM research in recent years has gradually widened in scope beyond these two original principles to cover all stages of the supply chain. To date, the literature offers various definitions of and terminologies for GSCM. They range from functional areas in the supply chain such as green purchasing (Chen 2005; Kannan et al. 2008) to green production (Rao 2004). Another key aspect of GSCM is in the integration of a supply chain associated with customers, manufacturers, disposals, and the closed-loop concept of reverse logistics (Zhu and Sarkis 2004; Hervani, Helms and Sarkis 2005; Rao and Holt 2005; Srivastava 2007; Sarkis, Zhu and Lai 2011). Other themes of research that have been defined as concerning GSCM include: environmental sustainability (Linton, Klassen and Jayaraman 2007; Zhu, Sarkis and Lai 2008), environmental management (Corbett and Klassen 2006; Vachon and Klassen 2008), ecological sustainability (King and Lenox 2001) and eco-efficiency (Huppes et al. 2007; Quariguasi Frota Neto et al. 2009). Figure 3-1 presents the origin of GSCM principles, recent definitions and terminologies.

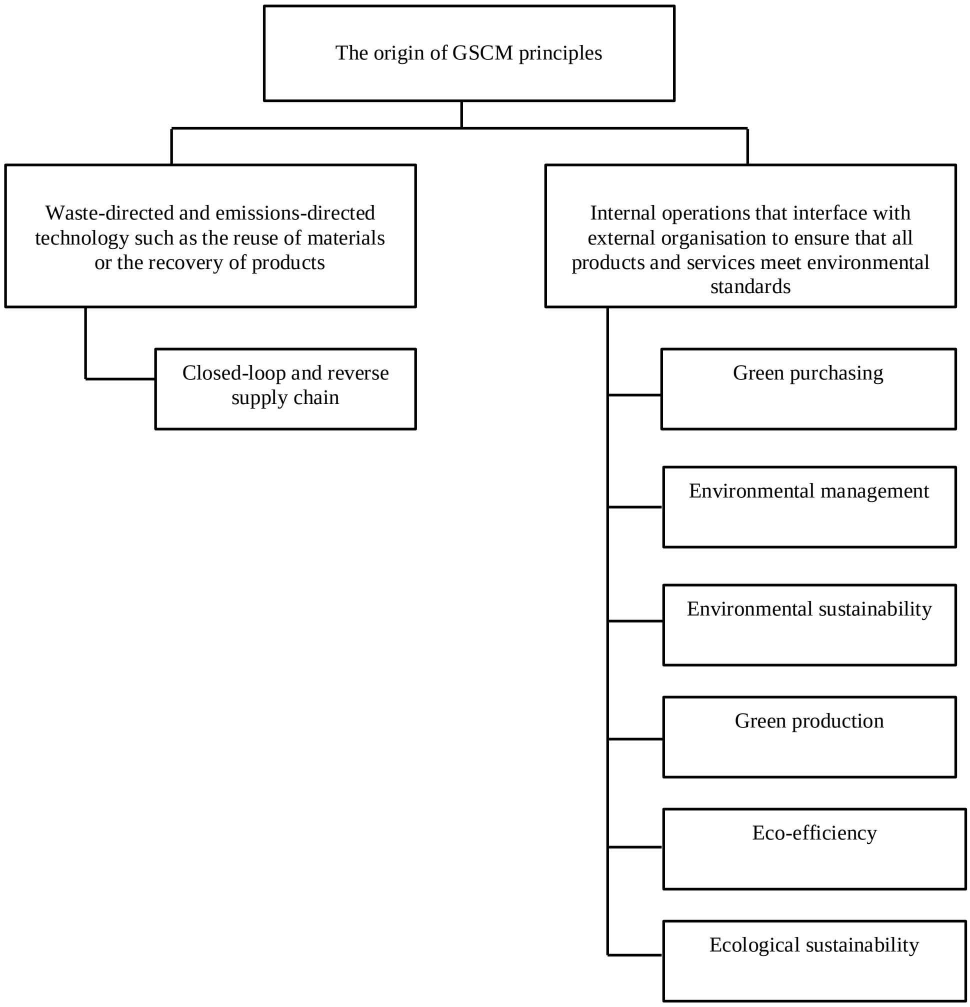

Figure 3-1: The origin of GSCM principles, recent definitions and terminologies

To integrate environmental concerns into the supply chain model, there is a need for an adequate GSCM model to deal with differing environmental criteria in the activities within the supply chain and in the decision-making process. In the following section, the modelling approaches in GSCM and its application to real-world problems will be reviewed. This section aims to provide insights into the choices regarding the appropriate GSCM modelling approach as it applies to the model developer.

3.4 MODELLING APPROACHES IN GREEN SUPPLY CHAIN MANAGEMENT

The literature pertaining to the modelling of GSCM is mostly divided into three approaches. The first approach uses a model for recycling and waste management that incorporates reverse-logistic activities for used products. The second approach concerns the development of a model for the design of the industrial supply chain network, where logistic activities are considered as a part of the whole operation. The third approach applies to the development of a model that is specific to the type of transport and route selection, without the incorporation of other logistical activities such as manufacturing or distribution.

3.4.1 Model for reverse-logistics and waste management

The first approach is concerned with the development of a model for recycling and waste management which incorporates reverse-logistic activities for used products. This approach has proven a fruitful area of research into GSCM and includes the work of Spengler et al. (1997), Barros, Dekker and Scholten (1998), Giannikos et al.(1998), Jayaraman, Patterson and Rolland (2003), Jayaraman (2006), Quariguasi Frota Neto et al.(2008), Quariguasi Frota Neto et al. (2009), and Gupta and Evans (2009).

Spengler et al. (1997) developed a mathematical model for recycling planning problems found within the steel industry. The model evaluates two planning recycle strategies: recycling of demolition waste, and recycling of products at the end of their life span. Barros, Dekker and Scholten (1998) proposed a two-level location model to manage recycling problems. In this research, the heuristic method was adopted to solve the model. The incorporation of a multi-objective optimisation model to deal with the disposal of hazardous waste and transportation can be found in Giannikos et al. (1998), and Jayaraman, Patterson and Rolland (2003). Giannikos et al. (1998)

developed goal-programming to solve this problem. Four objectives were considered in this model, including: (1) total costs; (2) risk; (3) equitable risk in each city; and (4) equitable disutility caused by waste operation. Jayaraman, Patterson and Rolland (2003) presented a reverse distribution model for hazardous and defective products which are harmful to the environmental. In this study, they assumed that the product had already been received by the customer. At the end of the product's useful life, customers have the option to return the used product to the collection point for reuse or recycling. The authors then developed an optimisation model to minimise the total costs of operating collection points and reuse/recycling facilities. Furthermore, Quariguasi Frota Neto et al. (2008) presented an efficient frontier concept of the industry with the trade-offs between costs and environmental criteria (wastes) being used in various scenarios regarding recycling legislation in the pulp and paper industry. Quariguasi Frota Neto et al. (2009) continued to explore the concept of trade-offs and efficient frontiers between costs and environmental criteria in their works. In this work, the author added a third objective function to investigate cumulative energy demand, in addition to the costs and wastes measures outlined in their earlier work.

Another concept involving reverse-logistics and waste management is a recoverable product environment or closed-loop system. This system focuses on extending the life cycles of products through the remanufacturing or repair process. Product flows in this system are considered from both a forward and a reverse supply chain perspective, as evidenced in the work of Sheu, Chou and Hu (2005), Jayaraman (2006), Schultmann, Zumkeller and Rentz (2006) , Du and Evans (2008) and Gupta and Evans (2009). Sheu, Chou and Hu (2005) presented a linear multi-objective programming model to optimise the operations of an integrated supply chain while incorporating the reverse logistics activities for used product. The author mentioned that the proposed model can improve the net profit by 21.1%. Jayaraman (2006) designed a closed-loop supply chain model for the remanufacturing of mobile phone products. The model is formulated to minimise the total costs of inventory, disassembly, disposal and the remanufacturing process. Similar work to Jayaraman (2006) can be found in Gupta and Evans (2009) and Schultmann, Zumkeller and Rentz (2006). Gupta and Evans (2009) developed an optimisation model for a closed-loop supply chain for multiple products, sub-assemblies, parts and raw materials. In order to solve the various problems, the research used a multi-criteria decision-making tool that dealt with multiple objectives. In Schultmann, Zumkeller and Rentz (2006), the author developed a model for end-of-life vehicles in Germany. The integration of vehicle routing planning in a closed-loop supply chain model was introduced to manage end-of-life vehicle materials backhauling. The objective of this research was to generate a transportation schedule with minimum costs. It can be seen that the research for this approach paid more attention to addressing the costs of the network. However, apart from financial parameters, there is evidence in Du and Evans (2008) which addresses network cycle time in reverse logistics. The authors focused closely on analysing reverse flows from post-sales services. A bi-objective optimisation model was formulated to capture the trade-offs between total costs and total time exceeding the cycle deadline. The results of this research suggest that a centralised network structure provides greater cost benefits while a decentralised network structure leads to a shorter cycle time.

3.4.2 Model for industrial supply chain network

The second approach is to develop a model for the industrial supply chain network. The model in this approach has as its primary focus, physical distribution processes such as manufacturing, distribution and transportation. Although transportation activity has been considered in these models, it has been deemed a marginal activity as the modes and routes selection for transportation decision-making are not included. This approach focuses more on the examination of the environmental impact with regard to the forward flow of products (Khoo et al. 2001; Ferretti et al. 2007). Khoo et al. (2001) created a GSCM model of the aluminium metal industry. They used a simulation-based approach which sought to balance costs and pollution by considering pollution from transport, marketing costs, lead-time, and scrap and energy usage. Ferretti et al. (2007) extended Khoo et al. (2001) 's work to develop a model for the green aluminium supply chain in which the economic variables were evaluated in terms of the level of pollution created. The idea was to first minimise total costs and then evaluate the total pollution produced.

Recent developments in this area have combined the traditional concept of the Life-Cycle Assessment (LCA) with the classical supply chain network design in order to monitor the environmental impact in the supply chain network. You and Wang, (2011) mention that LCA is the most common quantitative tool used for accounting for environmental burdens throughout the life-cycle of the product and process. The LCA analysis examines environmental impact in terms of raw materials, manufacturing, distribution, use, recycling and final disposal (Pinto-Varela, Barbosa-Povoa and Novais 2011). However, compared to the first approach, this approach's reverse flow activities are considered as constituting the whole supply chain network. Its key elements focus on the functional areas in the forward flow that facilitate the physical movement of products between supply chain partners. The applicability of different GSCM supply chain models in this approach has been studied intensively in industries such as the chemical industry(Hugo and Pistikopoulos 2005; Bojarski et al. 2009), the sugar cane industry (Mele et al. 2011) and the Biomass-to-electricity industry (Yue et al. 2014).

Hugo and Pistikopoulos (2005) presented a model for the chemical industry to assist in the strategic planning and design of a bulk chemical network. Their model is formulated to minimise the environmental impact resulting from operations in the entire network while simultaneously maximising the network's profitability. Bojarski et al. (2009) built on the work of the Hugo and Pistikopoulos (2005) model by applying it to the production of Maleic Anhydride (MA). The strategic decision factors in this model were facility location, processing technology selection and production and distribution planning. The authors developed the optimisation model for supply chain planning and design by incorporating economic and environmental issues. The results of the model provided information on different environmental policies and their impact upon each strategic decision criteria. In the sugar cane industry, Mele et al.(2011) developed a decision-support model for the design of an environmentally sustainable supply chain network which would maximise the net present value of the supply chain while minimising the environmental impact.

One model for GSCM in a sustainable supply chain context which addresses three objectives, i.e., economic, environmental and social, is found in Yue et al. (2014). They proposed a model to operate a bio-power supply chain which aims to optimise economic, environmental and social performance. In this model, the cost of electricity was chosen as the economic criteria, while the Life-Cycle Assessment examined the environmental impact. Jobs generated along the supply chain indicated fulfilment of social objectives.

3.4.3 Model for transportation mode and route selection

The third approach is to develop a model that is specifically applicable to the transportation mode and route selection. This model does not deal with other logistic activities such as manufacturing or distribution. Compared to the previous two approaches, the model in this approach has had little work conducted on it to date. Of the work that has been carried out, the most recent research focus has been on transportation activities at an operational level under the green logistics concept. Transportation activities include selection of vehicle types, delivery schedules, freight flow consolidation, and fuel type (Christie and Satir 2006; Ubeda, Arcelus and Faulin

2011). This research approach however, pays particular attention to road transport as evidenced in the work of Ubeda, Arcelus and Faulin (2011). Their research focused on environmental impact minimisation and the re-routing of food-distribution transport in Spain. In this study, three strategies of transportation system have been investigated to find the optimal transportation network that minimising total travelled distance and total CO_2 emissions ; (1) delivery-rescheduling; (2) backhauling; and (3) environmental optimisation. This research found that the best saving strategy from distance minimisation is rescheduling while backhauling appeared to be more effective in term of CO_2 emissions. Another research that attempt to estimate the CO_2 emissions reduction for road transport can be found in Christie and Satir (2006). This research supported Ubeda, Arcelus and Faulin (2011)'s work that delivery-rescheduling strategy can be used to reduce the energy consumption and environmental pollution.

Another more recent research focus in this approach is to calculate transportation costs and emissions, particularly with regard to the food supply chain; details may be found in the work of Soysal, Bloemhof-Ruwaard and van der Vorst (2014) and Validi, Bhattacharya and Byrne (2014). This approach, as applied to the food processing industry, has been influenced by the growing concerns of sustainability, quality preservation and environmental protection, these concerns must be balanced with the need to remain economically competitive (Soysal, Bloemhof-Ruwaard and van der Vorst 2014). Due to the characteristics of the product and transportation delivery options from this industry, road transportation is the main focus. Soysal, Bloemhof-Ruwaard and van der Vorst (2014) developed a model to investigate the beef supply chain in Brazil. The objectives of the model were to minimise total logistics costs while minimising total GHG emissions from transport operations. The transport operations in this research include road structure, vehicle and fuel types, weight load of vehicles, distances travelled, return hauls and perishablility. The research results indicate the importance of distances between supply chain members with regard to environmental impact. In addition, downturns in fuel efficiency due to poor road infrastructure have resulted in a negative impact on both costs and emissions. Conversely, green tax incentives for 3PL (Third Party Logistics service provider) to rent new trucks (with greater fuel efficiency) result in cost and emissions improvements. Validi, Bhattacharya and Byrne (2014) focused on analysing the downstream distribution of food products from producers to customers. The authors mention that downstream distribution transportation plays a significant role in the lowering of operating costs and the reduction of the impact upon the environment from the food supply chain. The role of green multi-objective optimisation models in minimising costs and environmental performance has been well-documented. The main parameters for the model are: truck type, fuel type, condition and type of road, and speed. The aim of this model was to optimise distribution transportation routes in the dairy market supply chain in Ireland with a view to minimising costs and CO_2 emissions. The results obtained presented the most feasible routes for the milk distribution system.

An emerging model design in this approach has been the integration of environmental criteria into the transportation mode and route selection. The transportation network is defined as intermodal transportation for various mode combinations such as road, rail and sea rather than a single mode of transportation (Winebrake et al. 2008; Kim, Janic and Wee van 2010). Winebrake et al.(2008) developed a model using ArcGIS network analysis and other software to design mode combinations and route selections to minimise energy use and CO_2 emissions in the eastern transportation corridor in the USA. Kim, Janic and Wee van (2010) developed a model which examined six scenarios for various routes in the East-West European transportation corridor with different market demands and freight mode capacities. The aim of the model was to estimate trade-offs between freight costs and CO_2 emissions.

In this study, freight costs represent economic criteria while CO_2 emissions indicate environmental criteria.

The classifications of the GSCM modelling approaches in this thesis literature review are presented in Table 3-1 below.

Table 3-1: Classifications of GSCM modelling approach.

GSCM modelling approach	**Description**	**Author**
1. Model for reverse- logistics and waste management	This approach aims to develop a model for recycling and waste management which incorporates reverse-logistic activities for used products. It also includes a recoverable product environment or a closed-loop system concept.	Spengler et al.(1997); Barros, Dekker and Scholten (1998); Giannikos (1998); Jayaraman, Patterson and Rolland (2003); Sheu, Chou and Hu (2005); Jayaraman (2006); Schultmann, Zumkeller and Rentz (2006); Du and Evans (2008); Quariguasi Frota Neto et al.(2008); Quariguasi Frota Neto et al.(2009); Gupta and Evans (2009)
2. Model for industrial supply chain network	This approach develops a model for the industrial supply chain network where logistics activities are considered. These activities have been deemed marginal where they do not include the mode and route selection for transportation decision-making. This approach focuses more on the examination of environmental impact with regard to the forward flow of product.	Khoo et al. (2001); Hugo and Pistikopoulos (2005); Ferreti et al. (2007); Bojarski et al. (2009); Wang, Lai and Shi (2011); Mele et al.(2011); You and Wang (2011); Yue et al. (2014)
3. Model for transportation model and route selection	This approach applies to the development of a model specifically for the type of transport and route selection without the incorporation of other logistics activities.	Christie and Satir (2006); Winebrake et al. (2008); Kim, Janic and Wee van (2010); Ubeda, Arcelus and Faulin (2011); Soysal, Bloemhof-Ruwaard and van der Vorst (2014) ; Validi, Bhattacharya and Byrne (2014)

3.4.4 Towards an integrated modelling approach to the development of the Thai Rubber GSCM

Chaabane et al.(2008) have argued that the models in the GSCM have been studied more from a recycling and waste management perspective than from an integrated supply chain network perspective. McKinnon (2010) also emphasised that there was a strong bias towards reverse logistics rather than forward logistics in the research into GSCM. These authors claim that the literature on GSCM (Sarkis 2003; Srivastava 2007) views transportation and distribution as a component in the broad GSCM system and focuses more on reverse flows. They pointed out that in real-world practice (Insight 2008), the companies that were successful in greening their supply chain had implemented their systems from a logistical activities point of view rather than by examining and utilising other elements in the chain. Further to this, from the previous section review, it appeared that there was little integration of the second and the third GSCM modelling approaches. A considerable amount of research has been undertaken into the second approach (Hugo and Pistikopoulos 2005; Ferretti et al. 2007; Bojarski et al. 2009), but in these works the transportation role was not considered explicitly in terms of including modes and route selection. The third approach is also lacking in that it either neglects to examine other components in the supply chain (Winebrake et al. 2008; Kim, Janic and Wee van 2010) or its narrative focus is only upon one mode of transportation (Ubeda, Arcelus and Faulin 2011; Soysal, Bloemhof-Ruwaard and van der Vorst 2014; Validi, Bhattacharya and Byrne 2014). Therefore, this thesis seeks to develop a GSCM model by integrating the second and third GSCM modelling approaches. It aims to contribute to the areas in the literature that are lacking. In addition, preliminary research into the Thai Rubber supply chain points to an unstructured supply chain network-flow (Kritchanchai 2009; Kritchanchai, Somboonwiwat and Chanpuypetch 2010) and high transportation costs (Wasusri and Chaichompoo 2008) as two of the major obstacles to competitiveness in the rubber industry. Environmental concerns from the worldwide rubber industry with regard to the weaknesses in the Thai Rubber require addressing. It is clear that research design is needed towards a supply chain network forward flow that includes transportation modes and routes selection, incorporates total costs and accounts for environmental pollution. Thus, the investigation into the forward chain also aims to contribute to providing a basis for a GSCM modelling framework, along with the formulation and development of further GSCM research and practices in this industry.

3.5 MATHEMATICAL TECHNIQUES IN THE GREEN SUPPLY CHAIN MANAGEMENT MODEL

GSCM problems are generally large scale and complex. They involve a large number of parameters, decision variables and constraints. Therefore, there is a need for sophisticated and powerful mathematical models and solution techniques to deal with these problems. Srivastava (2007) found that a diverse range of mathematical techniques for problem formulation and analysis have been adopted in GSCM research. With the use of these techniques, GSCM problems can be addressed, and integrates different activities and criteria, thereby improving the performance of the supply chain. A review of a variety of mathematical modelling techniques used for GSCM problem formulation can be found in Srivastava (2007).

According to the GSCM modelling approach discussed in the previous section, the principal mathematical techniques are characterised by simulation, heuristic, and optimisation-based modelling. The simulation method provides decision makers with tools to evaluate different scenarios (Terzi and Cavalieri 2004).The heuristic approach can be used as a complementary technique to reduce a problem to a manageable size until a better solution can be found (Coyle, Bardi and John Langley Jr 2003). The optimisation-based modelling approach is based on a mathematical formulation of the problem to find the optimum solution (Dantzig 2002).

The following section provides a brief overview of the mathematical techniques used in the GSCM model. The mathematical methods discussed have specific relevance to applications in the industrial supply chain and to transportation modes and routes selection in the GSCM modelling approach; these are the key modelling approaches developed in this thesis.

3.5.1 Simulation method

The simulation method is the process of creating a mathematical model to imitate the behaviour of a real-world process over time. It is used to provide a "what if" analysis of the operating system (Terzi and Cavalieri 2004). In GSCM research, simulation is commonly used for scenario generation and analysis (Srivastava 2007).

An example of research using the simulation method in the GSCM model developed for the industrial supply chain network may be found in Khoo et al. (2001). The authors created a simulation model to investigate the economic and environmental impact on the aluminium metal supply chain. The model was used to examine transportation pollution, marketing costs, time to market, recycling of scrap, and energy conservation for different choices of location and modes of transportation in the entire supply chain of four production plants. The authors pointed out that to create a reliable and robust simulation system, model developer has to focus on the accuracy of data, parameters and system behaviour.

Another research group used simulation method in GSCM is Teunter and Vlachos (2002). They developed simulation model to investigate the hybrid production system with manufacturing and remanufacturing under the assumption that "the remanufacturing would be profitable if there is more demand than return products in this system". The simulation model results are then used to analyse costs reduction from different return items. The results in this study shown that, disposal process is not necessary unless the demand is very low. Adhitya, Halim and Srinivasan (2011) presented a decision- making support tool to evaluate various environmental impacts on different supply chain network designs. Three scenarios of supply chain decisions related to changes in inventory composition, distribution network configuration and ordering policy were analysed. The disposable diaper business supply chain was selected to illustrate the methodology. The results obtained from this research found that restructures in inventory composition benefitted both economic and environmental performance. For network configuration, the results shown that the more distributors added, the higher of environmental impact and costs. In contrast, a less frequent ordering policy was deemed to reduce transportation costs and environmental pollution.

The simulation model developed to analyse the effect of information sharing in green supply chain can be found in Kainuma and Tawara (2006). In their model, supply chain with customer information and lead-time sharing is examined to compare with the supply chain with no information sharing. The simulation illustrated that supply chain with information sharing can decrease bullwhip effect and the out of stock ratio at the retailer.

For the food supply chain viewed from an ecosystem context, Jacxsens et al. (2010) analysed the impact of different logistic system designs on climate changes. The simulation model was used to investigate product quality, safety parameters and total costs in each packaging technology in order to anticipate changes in the logistics chain. The climate change impact of this research includes changes in extreme weather conditions, temperature, rainfall, food and waterborne diseases, and the environmental consequences of diminishing the location of crop product areas. The author has defined this model as a 'complex dynamic ecosystem'. Along with the simulation model of the fresh produce logistics chain, an optimisation model to optimise packaging technologies to maintain quality and product safety was presented. The results of this research provide insights towards a scenario analysis of fresh produce biological risk assessment and quality assurance guidelines.

The above research demonstrated how to develop a simulation model in GSCM research. It has been agreed that the simulation method is an efficient tool allow the decision maker to test the effect of alternative scenarios. However, the simulation model does not generate optimal solutions but evaluates the alternative options. Therefore, this method is not applicable for a model seeking “what is best” solutions. In some cases, the development of an effective simulation model may take considerable time and require a high level of programming along with a simulation program package, as mentioned in Khoo et al.(2001).

3.5.2 Heuristic method

The heuristic method is generally used as a complementary technique to solve mathematical programming models in GSCM. The use of the heuristic method can help to reduce a problem to a manageable size in order to find a better solution (Coyle, Bardi and John Langley Jr 2003). However, the heuristic method does not provide an optimum solution. Mula et al. (2010) mentioned that heuristics are mainly used in mixed-integer linear programming models and non-linear multi-objective models in complex supply chain problems. It is noticeable that the heuristic method has been used more widely for models developed for reverse logistics and waste management (Jayaraman and Ross 2003). Furthermore, Melo, Nickel and Saldanha-da-Gama (2009) highlighted that the heuristic method appeared to be the only technique suitable for solving the supply chain network problem in dealing with more than one facility layer for reverse logistics.

The example of research utilised heuristic method to solve the GSCM problem can be found in Jayaraman, Patterson and Rolland (2003). They used heuristic concentration procedure to manage the model's complexity to solve the problem in reverse logistics distribution in order to minimise the total reverse distribution costs. Another research adopted heuristic method to solve the model that integrate forward and reverse network flow is Ko and Evans (2007). They presented a mix-integer non-linear programming model for the design of 3PL warehousing and transportation operations. In addition, Quariguasi Frota Neto et al. (2009) employed two-phased heuristic method to solve their multi-objective linear problem. This model aimed to minimising total costs, cumulative energy demand and wastes in reverse logistics network. The author mentioned that heuristic method could be used to overcome the drawback of multi-objective optimisation problem in terms of CPU-time intractability and visual representation for a large size variables and parameter from case study.

In the industrial supply chain network modelling approach, the heuristic method has been adopted to solve problems related to facility locations, as evidenced in the work of Lee and Dong (2008). They discussed a logistics network design for computer product recovery to minimise the total costs of and the total environmental impact upon the logistics network. Due to the complexity of such a network design problem, a heuristic approached was selected to solve the proposed model, and this incorporated the locations of depots and the construction of a feasible solution for the shipment of products.

3.5.3 Optimisation-based method

The optimisation-based method is based on the mathematical procedures that are guaranteed to find the optimum solution under a given set of relevant assumptions, constraints and data (Coyle, Bardi and John Langley Jr 2003). In order to do this, the model must incorporate different mathematical programming techniques such as linear programming (LP), mixed-integer programming (MIP), and non-linear programming (NLP) to solve the model (Dantzig 2002).Many of these mathematical programming techniques for optimisation models have been incorporated into software packages such as Lingo and CPLEX which are commercially available for solving large-scale supply chain models.

In the existing literature, linear programming has enabled the modelling of many GSCM problems, as evidenced in the work of Sheu, Chou and Hu (2005). They presented a linear multi-objective programming model that optimises the operations of an integrated supply chain of computer products. The author pointed out that the proposed model conveyed two significant outcomes: (1) a general mathematical model that may be used in any industrial case study and (2) a 21.1% improvement in the operations costs of the supply chain.

In addition, GSCM model in food product industry is conducted in Soysal, Bloemhof-Ruwaard and van der Vorst (2014). They proposed a linear multi-objective programming model for a generic beef supply chain in Brasil to minimising total logistics costs and GHG emissions. Total logistics costs and GHG emissions are measured by following activities; inventory, transportation of fully and less than fully loaded trucks for road transport and transportation of other modes such as rail, air and ocean between departure and arrival points.

Since linear programming applicability is limited, due to the need for the problem formulation to be one of linear approximation, mixed-integer linear programming (MILP) has been used to address this limitation for models dealing with issues related to fixed and variable costs and economies of scale (Coyle, Bardi and John Langley Jr 2003). In the MILP formulation, continuous variables are used to represent material flows while binary variables are used to indicate decisions such as the selection of facilities or the type of transport. This MILP is mainly used to find the optimal configuration for the supply chain network. The use of MIP in the GSCM model can be found in Hugo and Pistikopoulos (2005), Bojarski et al. (2009) and Wang, Lai and Shi (2011).

3.5.4 Mathematical techniques for the Thai Rubber GSCM model

This thesis aims to develop a decision-support model for the Thai rubber industry. Therefore, the use of appropriate mathematical modelling techniques will be crucial to the formulation and development of the model design. While all the mathematical techniques described above can be used to pursue the development of the model, the method of choice will be the one that is able to provide optimal solutions whilst including the "what is best" analysis tool. The model must: (1) be simple, easily described to the decision maker in order for them to understand both techniques and solutions; (2) have a solution software that is commercially available; and (3) be time-saving in its problem formulation and solution procedure.

The method that allows for such problem formulation and solution analysis is the optimisation method. de Boer, labro and Morlacchi (2001) state that in solving a problem, the best choice from among a set of alternatives may be that of the optimisation technique. Bloemhof-Ruwaard et al. (1995) also pointed out that the optimisation method appears to be effective as a tool to cover complex systems in GSCM problems which deal with costs, emissions, transportation and control policies. In addition, Srivastava (2007) found that linear programming is the most utilised technique in GSCM problem formulation. This technique has been used to solve GSCM problems regarding linking the facilities in a network where supply and demand are limited in each supply chain entity. The technique can be used to represent capacities that avoid nonlinearities. As such, this thesis proposes the use of the linear programming optimisation technique for problem formulation in the Thai Rubber GSCM model.

The linear programming is concerned with the maximisation or minimisation of a linear objective function. It is determined the values of the variables of the system that are satisfy a system of linear constraints and are non-negative (Dantzig 2002). An overview of a history of the development of linear programming as a mathematical programming tool in various application, see Dantzig (2002). The general linear programming problem formulation refer to Downsland (2005).

The linear optimisation technique can be classified into two categories: single-criteria/objective models and multi-criteria/objective models. The following section provides a brief overview on these two modelling methods in various GSCM model applications.

3.5.4.1 Single-criteria/ objective model

The first approach in the linear programming model considers that the GSCM problem has one objective function requiring optimisation. This approach to traditional supply chain management was originally influenced by economic objectives in terms of cost or profit (Chaabane, Ramudhin and Paquet 2012).With regard to environmental problems, the existing literature contains evidence of an early attempt to use single objective optimisation in Batta and Chiu (1988). They developed two single objective formulations for hazardous waste routing. In the model, one criterion included the size of the population which would be potentially impacted upon by an accidental release of hazardous waste. The authors also mentioned the difference in risk between network nodes and network links by assigning penalties to nodes and considering different accident probabilities for different links in the network. Due to the limitation of single objective optimisation to address environmental problem, single objective optimisation model seems to be obsoleted method from the literature.

To incorporate environmental concerns into supply chain management, the decision-making model must address additional trade-offs, particularly those between economic and environmental impact criteria. The above authors suggested that the multiple-criteria model is essential as a potential tool for further exploration in this area, and this has led to the development of the multi-objective optimisation model. Recent developments in GSCM research have further shifted to include multi-objective optimisation in considering environmental criteria, particularly in relation to costs, as a design objective, along with other objectives.

In the following section, multi-objective optimisation used in GSCM research is introduced and discussed.

3.5.4.2 Multi-criteria/objective model

The second approach in linear optimisation techniques formulates GSCM problems as corresponding to more than one specific objective, subject to defined constraints. The use of this model requires the incorporation of environmental performance which must be optimised in conjunction with economic criteria. As a result, the objective function for multi-objective optimisation in the GSCM problem focuses particularly on minimising total costs or maximising total profit while simultaneously minimising total environmental pollution (Hugo and Pistikopoulos 2005; Buddadee et al. 2008; Kim, Janic and Wee van 2010; Guillén-Gosálbez, Mele and Grossmann 2010; Wang, Lai and Shi 2011). In these research, total costs are generally the summation of supply chain activities costs such as production costs, inventory costs, and transportation costs (You and Wang 2011; Yue et al. 2014) while total profit is expressed in terms of net profit values (Hugo and Pistikopoulos 2005). For environmental impact objectives, various measures have been developed to indicate environmental performance in the GSCM model, such as CO_2 emissions (Kim, Janic and Wee van 2010; Wang, Lai and Shi 2011; Soysal, Bloemhof-Ruwaard and van der Vorst 2014) ,GHG emissions (You and Wang 2011; Chaabane, Ramudhin and Paquet 2012; Yue et al. 2014), energy consumption (Winebrake et al. 2008) and Global Warming Potential (Buddadee et al. 2008).

Recent research which has adopted the multi-objective optimisation technique as a tool to develop decision-support model in Thailand is that of Buddadee et al.(2008). This research investigated the Thai sugar cane supply chain in order to provide the decision maker with information regarding the following: (1) location and size of the ethanol production plants; (2) the allocation of bagasse from each sugar mill to the corresponding ethanol plant. In this study the Global Warming Potential (GWP) objective is used to represent the impact of the emissions of all GHGs, while economic objectives are the summation of all operational costs. The weighting method was adopted to solve this model. The results obtained from this research show the selected potential sites for ethanol plants with various weightings allocated to GWP and to economic factors. The advantage of the multi-objective model over the single objective model is that this method provides trade-offs between conflicting objectives. Quariguasi Frota Neto et al. (2008) and Quariguasi Frota Neto et al.(2009) mention that achieving a win-win solution between the environment and the economy is difficult in practice. They therefore suggest seeking effective trade-offs as the ultimate solution for real-world practices. This suggestion has led to the Pareto optimal concept. By definition, the Pareto is a set where none of the objective functions can be improved without worsening the value of another objective function (Caramia and Dell'Olmo 2008, 20). Therefore, the Pareto set of solutions offers a range of alternative solutions; the decision maker can investigate and select the supply chain network design that most satisfies their preferences. An overview of multi-objective optimisation and Pareto optimal solutions can be found in Chapter 6.

Wang, Lai and Shi (2011) created a green supply chain model by incorporating a new decision variable called the “environmental protection level” in the design phase. This variable represents the value of environmental investment that could lead to the lowering of CO_2 emissions. The Pareto optimal curve in each scenario shows trade-offs between CO_2 emissions and investment costs. The results also provide a portfolio of supply chain network configurations for the decision-making process. The research found that improving the capacity of the network and increasing the amount of supplies to the facilities decreased CO_2 emissions and total costs for the whole supply chain network. In addition, they pointed out that an environmental care program is necessary and that it would be more effective at the higher demand level.

Another research group exploring the concept of the Pareto optimal solution is You and Wang (2011). They developed the mixed integer multi-objective optimisation model to optimise the design of the biomass-to-liquid (BTL) supply chain in order to simultaneously minimise economic and environmental pollution. The multi-objective model in this research was solved by using the ε -constraint method to produce a Pareto curve to represent the trade-offs between optimal costs and environmental performance in the BTL supply chain. Similar research to You and Wang (2011) in biomass supply chain can be found in Yue et al. (2014). The author developed a multi-objective, multi-period mixed integer linear fractional programming model to design and operate bio-power supply chain. However, to extended You and Wang (2011) ’s work, this research have added the third objective; social impact along with economic and environmental to optimise. The ε -constraint method is adopted to calculate Pareto curve trading off between economic and environmental impacts and economic and social impacts in the bio-power supply chain. Soysal, Bloemhof-Ruwaard and van der Vorst (2014)’s work focus to seeking for a trade-offs between total logistics costs and GHG emissions from transportation operation along the supply chain. The results of this research suggest that decreasing emissions from transportation lead to a higher logistics costs. However, the ratio of new truck usage shows positive impact to total emissions.

Kim, Janic and Wee van (2010) have conducted work on transportation modes and route selection in a GSCM modelling approach that focuses on estimating the trade-offs between freight costs and CO_2 emissions. In their model, multi-objective optimisation is used as a decision-support tool to find the optimal freight system and the trade-offs between these two objectives. This research examined six scenarios for various routes in the east-west European corridor with different market demands and freight mode capacities. The results showed that the trade-off curves tended to have a linear relationship with freight costs and CO_2 emissions. This implied that freight costs should be higher as a reduction in CO_2 emissions was required. The study also showed that an increase in the processing capacity of the CO_2 emitting system could lead to a reduction in CO_2 emissions. Validi, Bhattacharya and Byrne (2014) developed a model to design the distribution routes of diary supply chain producing milk products that simultaneously minimising total costs and CO_2 emissions from outbound distribution and transportation. The results suggested the feasible transportation routes that trade-offs between costs and CO_2 emissions. Simulation method is subsequently used to analyse the impacts from operating these routes to costs and CO_2 emissions.

The above review stresses that the trade-offs between economic and environmental objectives must be considered in the design of the supply chain model. This will assist decision-makers to manage their supply chains as successful green practices and profitable enterprises. Table 3-2 presents mathematical techniques in GSCM model which have specific relevance to the applications in the industrial supply chain and to the transportation modes and routes selection in the GSCM modelling approach (see table 3-1); these are the key modelling approaches developed in this thesis.

Table 3-2: Mathematical techniques in GSCM model

Mathematical Techniques in GSCM model	**Author**	
1. Simulation	Khoo et al. (2001); Teunter and Vachos (2002); Kainuma and Tawara (2006); Jacxsens et al. (2010)	
2. Heuristic	Jayaraman, Patterson and Rolland (2003); Ko and Evans (2007); Quariguasi Frota Neto et al.(2009) ; Lee and Dong (2008)	
3. Optimisation-based method	Single-criteria/objective model	Batta and Chua (1988)
	Multiple criteria/objectives model	Sheu, Chou and Hu (2005); Hugo and Pistikopoulos (2005); Buddadee et al. (2008); Bojarski et al. (2009); Kim, Janic and Wee van (2010); Wang, Lai and Shi (2011); You and Wang (2011); Yue et al. (2014); Validi, Bhattacharya and Byrne (2014); Soysal, Bloemhof-Ruwaard and van der Vorst (2014)

3.6 SUMMARY

In this chapter, a literature review of past and emerging issues regarding GSCM modelling approaches and mathematical techniques used to develop the GSCM model has been presented. The extensive literature review concluded that research into the improvement of the GSCM model design must include transportation modes and route selection along with the incorporation of costs and environmental criteria. The research utilises this proposed modelling approach and aims to fill gaps in the research field and provide an appropriate decision-support model for the Thai Rubber industry.

Although several mathematical techniques can be used to pursue GSCM model development, the optimisation-based method is accepted as the most appropriate model choice. This is due to its simplification, low time consumption for problem formulation, and variety of effective software to solve the model. William (1990) mentioned that an efficient model need not necessarily be a complex one. He suggested that a sound model can be developed based on ease of understanding, ease of detecting errors and ease in computing the solution. With this in mind, the goal of this thesis is not to develop a complex or entirely new mathematical method and solution approach. Instead, it attempts to take advantage of previously developed techniques and apply them to the Thai Rubber industry supply chain.

Finally, the above review has shown that Green Supply Chain Management is accepted as a new management tool to create a positive compromise between 'Planet and Profit' as stated in Quariguasi Frota Neto et al. (2008). Various GSCM decision-support models in the literature also highlight that there are opportunities to utilise the methodology in this thesis to broaden the case studies from the Thai Rubber industry so that they may contribute to global GSCM research communities.

CHAPTER 4

AN OPTIMISATION MODEL

FOR THE THAI RUBBER SUPPLY CHAIN[5] [6]

4.1 INTRODUCTION

This chapter focuses on the design of a Green Supply Chain Management (GSCM) model for the Thai Rubber industry. GSCM problems are generally large scale and complex, involving a great number of parameters, decision variables and constraints. Therefore, appropriate mathematical modelling techniques are essential for the creation of effective model designs and formulations which will address the current issues in the industry supply chain.

This chapter will thus use the optimisation-based method as the preferred methodology. It will formulate the model by incorporating the production, distribution and

[5] Part of this chapter has been presented at the following conferences: 1) Chanchaichujit, Janya, Quaddus Mohammed, West Martin, and Saavedra-Rosas Jose. 2012. *"An optimization based decision support model for the Thai rubber industry supply chain : Preliminary results"* Paper presented at *International Conference on Industrial Engineering and Engineering Management (IEEE2012), Hong Kong, 10-13 December.*; 2) Chanchaichujit, Janya, Quaddus Mohammed, West Martin, and Saavedra-Rosas Jose. 2013. "Green supply chain model for the Thai rubber industry". Paper presented at *The 18th International Symposium on Logistics, Vienna, Austria, 7-10 July.*

[6] Part of this chapter has been submitted to International Journal of Logistics Management. Chanchaichujit, Janya, Quaddus Mohammed, West Martin, and Saavedra-Rosas Jose. "Green supply chain model for the Thai rubber industry" *International Journal of Logistics Management* (Revised and resubmitted July 2014)

transportation of rubber products in such a way that total costs and total greenhouse gas emissions will be minimised. The initial stage of this thesis will develop the GSCM model by formulating costs and GHG emissions as two single objective functions. The objective function of minimising total costs represents economic performance, while minimising total GHG emissions indicates environmental performance. Since this thesis is among one of the first studies to develop a GSCM model for the Thai Rubber supply chain, its development from a single objective model will be a basis for a modelling framework. Its aim is to provide a comprehensive understanding of the basic elements of the model in relation to costs and greenhouse gas emissions. In this chapter, a single objective optimisation model will be developed and the results analysed, while the following chapters will take a further step by adding another degree of complexity based on this model framework.

The chapter is organised as follows. Firstly, the Thai Rubber supply chain problem formulation and framework is introduced. Following this, the model notation and mathematical formulation are presented. In order to validate the model, model validation and sensitivity analysis will be performed. The chapter concludes with the model results and summary.

4.2 PROBLEM FORMULATION

As mentioned in Chapter 2, the Thai Rubber supply chain consists of fourteen province divisions in Southern Thailand. These are made up of: Trang, Pattalung, Satun, Songkhla, Pattani, Yala, Narathiwat, Chumporn, Ranong, Suratthani, Phangnga, Nakhon Si Thammarat, Krabi, and Phuket. The fourteen provinces represent 79% of total Thai Rubber production (TRA 2010). The farmers' rubber group is classified according to the plantation areas each farmer occupies. There are three sizes of Thai Rubber farm; small, medium, and large. Three types of primary rubber products were examined in this model: unsmoked sheet (US), cup-lump (CL) and field latex (LX). These products are the raw materials used to produce the intermediate rubber products of: ripped-smoke sheet (RSS), block rubber (STR), and latex concentrate (LCT) respectively. There are three trader groups in Thailand: general market (GM), cooperative (CO) and dealer (DL). The Thai Rubber supply chain is based upon a model framework as depicted in Figure 4-1.

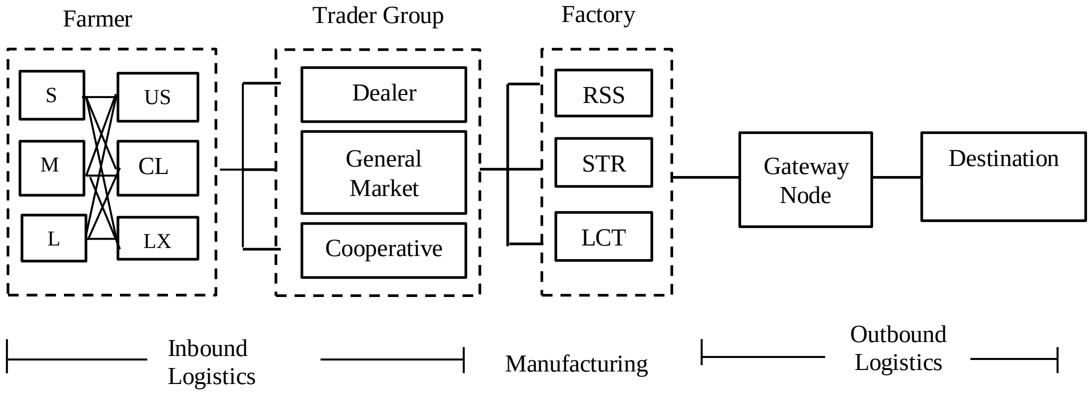

Figure 4-1: The Thai Rubber supply chain model framework

The inbound rubber supply deals with the primary rubber products produced by each size of farm before being sold through local market traders in each province. The market traders then deliver the primary rubber products down the chain to the factories, with each factory in each province processing the intermediate rubber products. Outbound distribution flow consists of activities related to the transportation of intermediate rubber products from the factory through the gateway node to various destinations. The outbound distribution flow is defined as the intermodal freight transport network. It comprises different combinations of freight modes such as road-rail-sea. Gateway nodes in this model represent the rubber activities centres for trading and exporting. In addition to being the centre of rubber activities, gateway nodes also have intermodal terminals that handle regional rubber product shipments for domestic consumption and export. These intermodal terminal hubs for rail and inland waterways service the shipments to major ports in Thailand and Malaysia. The three gateway nodes are Songkhla, Suratthani and Nakhon Si Thammarat province. In addition, there are fourteen possible routes in these outbound distribution transport networks as shown in Figure 2-8 in Chapter 2. At the end of the chain, supplies become domestic stock, are used for domestic consumption or are sent to exporting ports including Laemchabang, Bangkok, Songkhla and Penang.

4.3 MODEL NOTATION AND DATA

This section describes the sets, parameters, and decision variables used in the model. The following assumptions were made in designing the model:

- The objective function and constraints are expressed in the form of linear relationships of the decision variables;
- All costs are assumed to be fixed costs; and
- All parameters such as farmer production, manufacturing production, demand, costs and GHG emissions are known (or can be estimated) in advance.

4.3.1 Data collection and triangulation

The model in this chapter has been developed through investigation into the problems within the Thai Rubber industry. The data was collected from primary and secondary data sets published in the public domain, such as Thailand Agricultural Statistics (OAE 2011), Thailand Rubber statistics (RRI 2011) and Thailand Rubber reports (TRA 2010). Some of the model data was taken from existing literature. See Table A-1 to A-15 in Appendix for variable and parameter values used in this thesis.

In addition, interviews were conducted to obtain some primary data sets and for data triangulation to validate the secondary data sets taken from published sources.

4.3.2 Model notation

Sets, parameters, and decision variables are defined as follows:

Set

$i \in I$	Set of provinces
$p \in P$	Set of primary rubber products
$s \in S$	Set of rubber farm sizes
$t \in T$	Set of truck types
$g \in G$	Set of trader groups
$f \in F$	Set of factories
$e \in E$	Set of intermediate rubber products
$a \in A$	Set of gateway nodes
$b \in B$	Set of intermodal freight routes
$d \in D$	Set of domestic destinations and exporting ports
α	Mixing parameter

Decision Variables

X_{isptg}	Amount of primary rubber product p produced from farm size s in province i transported by truck type t to trader group g
Y_{igfea}	Amount of primary rubber product p from trader group g in province i transported to factory f to produce intermediate rubber product e and subsequently transported to gateway node a

Z_{eabd}	Amount of intermediate rubber product e from gateway node a transported by intermodal freight route b to domestic destination and exporting port d

Data and Parameters

SC_{si}	Aggregated primary rubber cultivation capacity of farm size s in each province i
TGC_{gpt}	Aggregated trader group capacity of a given trader group g for primary rubber product p in each province i
FC_{fe}	Aggregated factory production capacity of intermediate rubber product e in a given factory f
DNC_a	Aggregated gateway node capacity in a given gateway node a
FRC_b	Aggregated freight route capacity for a given freight route b
DE_{de}	Aggregated demand of intermediate rubber product e at destination d

Cost Parameters

CR_{sp}	Cost to farm size s of processing primary rubber product p
CT_{stg}	Cost of transporting primary rubber product from farm size s to trader group g by truck type t
CG_{gp}	Cost of trading primary rubber product p in trader group g
CT_{igf}	Cost of transporting primary rubber product from trader group g in province i to factory f
CF_{fe}	Cost to factory f of processing intermediate rubber product e

CT_{fa} Cost of transporting intermediate rubber product from factory f to gateway node a

CT_{ab} Cost of transporting intermediate rubber product from gateway node a to freight route b

CM_b Cost of exporting intermediate rubber product via freight route b

CT_{bd} Cost of transporting intermediate rubber product from freight route b to destination d

Environmental Parameters

ER_{sp} GHG emissions from farm size s to process primary rubber product p

ET_{stg} GHG emissions from transporting primary rubber products from farm size s to trader group g by truck type t

EG_{gp} GHG emissions from trading primary rubber product p in trader group g

ET_{igf} GHG emissions from transporting primary rubber product from trader group g in province i to factory f

EF_{fe} GHG emissions from factory f to process intermediate rubber product e

ET_{fa} GHG emissions from transporting intermediate rubber product from factory f to gateway node a

ET_{ab} GHG emissions from transporting intermediate rubber product from gateway node a to freight route b

EM_b GHG emissions from exporting intermediate rubber product via freight route b

ET_{bd} GHG emissions from transporting intermediate rubber product from freight route b to destination d

4.4 MATHEMATICAL FORMULATION

The Thai Rubber supply chain is presented in terms of a mathematical formulation with two single objective functions. Linear programming was chosen as the mathematical programming for investigation into the problem of finding the association of the quantity of rubber product flow between the supply chain entities (farmer, trader group, and factory) and the transportation mode and route, with a view to minimising total costs and total greenhouse gas emissions.

Objective functions and constraints for the Thai Rubber supply chain mathematical formulation are presented as follows:

4.4.1 Objective functions:

Objective function (1) is to minimise the total costs of: farm processing for primary rubber products, trader group operations, factory processing of intermediate rubber products and factory export of intermediate rubber products. Included in the objective is the minimising of the total costs of transportation which include the cost of transport from: farmer to trader group, trader group to factory, factory to gateway node, gateway node to freight route, and transport from freight route to destination.

$$Min\ Z_1 =$$

$$\sum_i \sum_s \sum_p \sum_t \sum_g X_{isptg}(CR_{sp} + CT_{stg} + CG_{gp}) +$$
$$\sum_i \sum_g \sum_f \sum_e \sum_a Y_{igfea}\left(CT_{igf} + CF_{fe} + CT_{fa}\right) +$$
$$\sum_e \sum_a \sum_b \sum_d Z_{eabd}(CT_{ab} + CM_b + CT_{bd}) \qquad (1)$$

Objective function (2) is to minimise the total GHG emissions from the same activities as per above objective function (1).

$$Min\ Z_2 =$$

$$\sum_i \sum_s \sum_p \sum_t \sum_g X_{isptg}(ER_{sp} + ET_{stg} + EG_{gp}) +$$
$$\sum_i \sum_g \sum_f \sum_e \sum_a Y_{igfea}\left(ET_{igf} + EF_{fe} + ET_{fa}\right) +$$
$$\sum_e \sum_a \sum_b \sum_d Z_{eabd}(ET_{ab} + EM_b + ET_{bd}) \qquad (2)$$

4.4.2 Constraints:

Farmer cultivation capacity:

This constraint is the capacity constraint on rubber farm production. It identifies that the sum of primary rubber products p produced from farm sizes s in provinces i transported by truck type t to trader group g must be less than or equal to the primary rubber cultivation capacity of farm size s in each province i

$$\sum_p \sum_t \sum_g X_{isptg} \leq SC_{si} \quad , \forall s \in S , \forall i \in I \qquad (3)$$

It has been observed from the Thai Rubber industry practice that farmer can judge what level of production they should produce the primary rubber product. The main factor influences farmer decision is rubber price. Farmer may lower their farm production capacity if rubber price is low. On the other hand, they can increase the farm production capacity when rubber price is higher. Lower or fully utilised capacity at the farmer level usually happens as a reflection of rubber price movement. It can be noted that the nature of farmer level production capacity is different from process level capacity as the resources used to produce primary rubber product are only rubber tree and labour. Therefore, farmer cultivation capacity is flexible and adjustable without created any significance consequences to the rubber industry.

Trader group capacity:

This is the constraint upon trader group capacity. It identifies that the sum of primary rubber product p produced from farm size s in province i transported by truck type t to trader group g must be less than or equal to the sum of the trader group capacity of a given trader group g for primary rubber products p in each province i

$$\sum_s \sum_t X_{isptg} \leq TGC_{gpi} \quad , \forall g \in G , \forall p \in P , \forall i \in I \qquad (4)$$

Factory production capacity:

This is the constraint upon factory production capacity. It identifies that the sum of primary rubber products from trader group g in province i transported to factory f to produce intermediate rubber products e subsequently transported to gateway node a must be less than or equal to the sum of the factory production capacity of intermediate rubber products e in a given factory f

$$\sum_i \sum_g \sum_a Y_{igfea} \leq FC_{fe} \quad , \forall f \in F , \forall e \in E \qquad (5)$$

Gateway node capacity:

This is the constraint upon gateway node capacity. It identifies that the sum of primary rubber products from trader group g in province i transported to factory f to produce intermediate rubber products e subsequently transported to gateway node a must be less than or equal to the sum of the gateway node capacity in a given gateway node a

$$\sum_i \sum_g \sum_f \sum_e Y_{igfea} \leq DNC_a \quad , \forall a \in A \qquad (6)$$

Freight system capacity:

This is the constraint upon the capacity of the freight system. It identifies that the sum of intermediate rubber products e from gateway node a transported by intermodal freight route b to destination d must be less than or equal to the sum of freight route capacity in a given freight route b

$$\sum_e \sum_a \sum_d Z_{eabd} \leq \ FRC_b \quad , \forall b \in B \tag{7}$$

Demand:

This is the constraint regarding demand. It identifies that the sum of intermediate rubber products e from gateway node a transported by intermodal freight route b to destination d must be less than or equal to the sum of demand for intermediate rubber product e at destination d

$$\sum_a \sum_b Z_{eabd} = \ DE_{de} \quad , \forall d \in D \,, \forall e \in E \tag{8}$$

Production product mix ratio:

The following constraints define the primary rubber product mix ratio (α and $1-\alpha$) required to produce intermediate rubber products. In this thesis, α is defined as 0.2. Raw material amounts of 0.2 of US and 0.8 of CL are mixed to produce STR. US is the only raw material to produce RSS while LCT uses only LX for the production (STA 2012b).

$$\alpha * \left(\sum_i \sum_g \sum_f \sum_a Y_{igf\text{"STR"}a}\right) + \left(\sum_i \sum_g \sum_f \sum_a Y_{igf\text{"RSS"}a}\right) = \sum_i \sum_s \sum_t \sum_g X_{is\text{"US"}tg} \quad , \ \forall e \in E \,, \forall p \in P \tag{9}$$

$$(1-\alpha) * \left(\sum_i \sum_g \sum_f \sum_a Y_{igf\text{"STR"}a}\right) = \ \sum_i \sum_s \sum_t \sum_g X_{is\text{"CL"}tg} \quad , \forall e \in E, \forall p \in P \tag{10}$$

$$\left(\sum_i \sum_g \sum_f \sum_a Y_{igf\text{"LCT"}a}\right) = \sum_i \sum_s \sum_t \sum_g X_{is\text{"LX"}tg} \quad (11)$$

Conservation flow:

The following constraints are defined to ensure the balance flow:

$$\sum_i \sum_s \sum_p \sum_t X_{isptg} = \sum_i \sum_f \sum_e \sum_a Y_{igfea} \qquad , \forall g \in G \quad (12)$$

$$\sum_i \sum_g \sum_f Y_{igfea} = \sum_b \sum_d Z_{eabd} \qquad , \forall e \in E, \forall a \in A \quad (13)$$

Non-negativity constraints:

$$X_{isptg} \geq 0 \quad (14)$$

$$Y_{igfea} \geq 0 \quad (15)$$

$$Z_{eabd} \geq 0 \quad (16)$$

4.5 MODEL VALIDATION

In order to validate the model developed for the Thai Rubber supply chain, a validation test was performed on the linear programming model. This is usual, in order to ensure that the model correctly and accurately represents real world behaviour (McCarl and Apland 1986). McCarl and Spreen (2004) divided model validation into validation by construct and validation by results. Validation construction justifies that the model was developed by following correct procedures, while validation by results aims to ensure that the model results accurately represent real world values.

In this chapter, validation tests on both construct and results were performed. The validation by construct was undertaken by using a process of model development and mathematical formulation, following the structure procedure that is relevant in linear programming. Therefore, the construct of the model developed in this chapter is validated

(McCarl and Spreen 2004). However; we have mainly focussed on validation of the process known as validation-by-result.

The validation by result was performed by comparing the baseline model results to observed real world values. The model values were derived by running the baseline scenario model, while the real world values were those observed by a group of experts in the Thai Rubber industry. The experts included two production managers from the leading Thai Rubber companies, senior government officers in the Thai Rubber Association, and academics in the office of Agricultural Economics, Ministry of Agriculture and Cooperative. The real world values assume that current trends in the global rubber industry will continue and that there will be no new external interventions in the Thai Rubber industry. Examples of current trends include rubber demand, rubber prices, and rubber production yields. External interventions include new breakthroughs in factory production technology, new government trading mechanisms and new transport infrastructure such as railways and seaports.

The comparison of baseline model results and observed real word values was conducted and compared for three major decision variables defined in the model: X_{isptg}, Y_{igfea} , Z_{eabd} (see section 4.3 for decision variables description). To quantify the match of each decision variable, a graphical comparison is presented in Figure 4-2, 4-3 and 4-4.

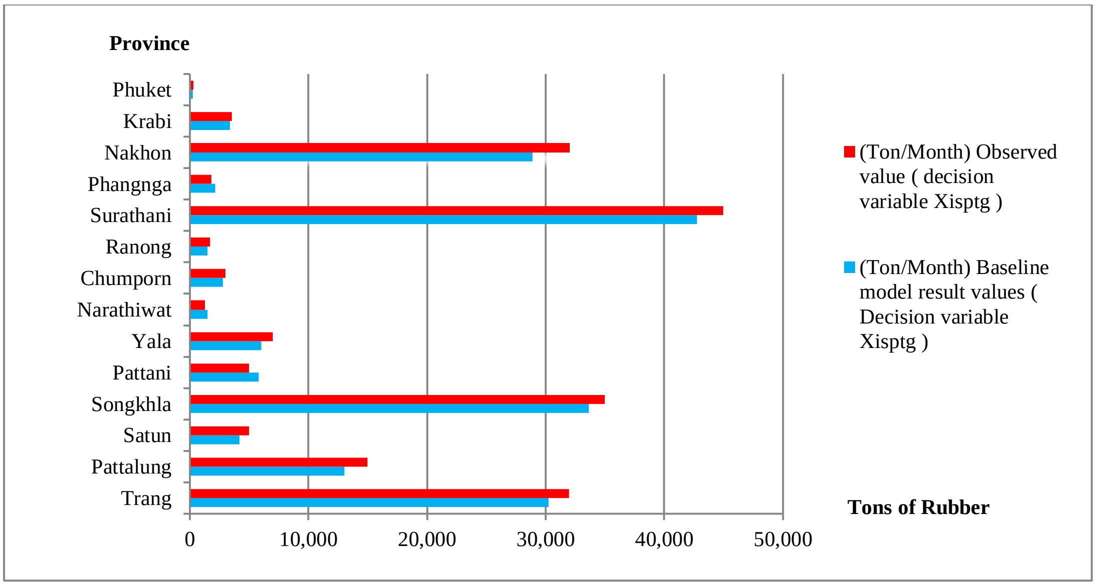

Figure 4-2: A comparison between baseline model results and observed real world values for decision variable X_{isptg}

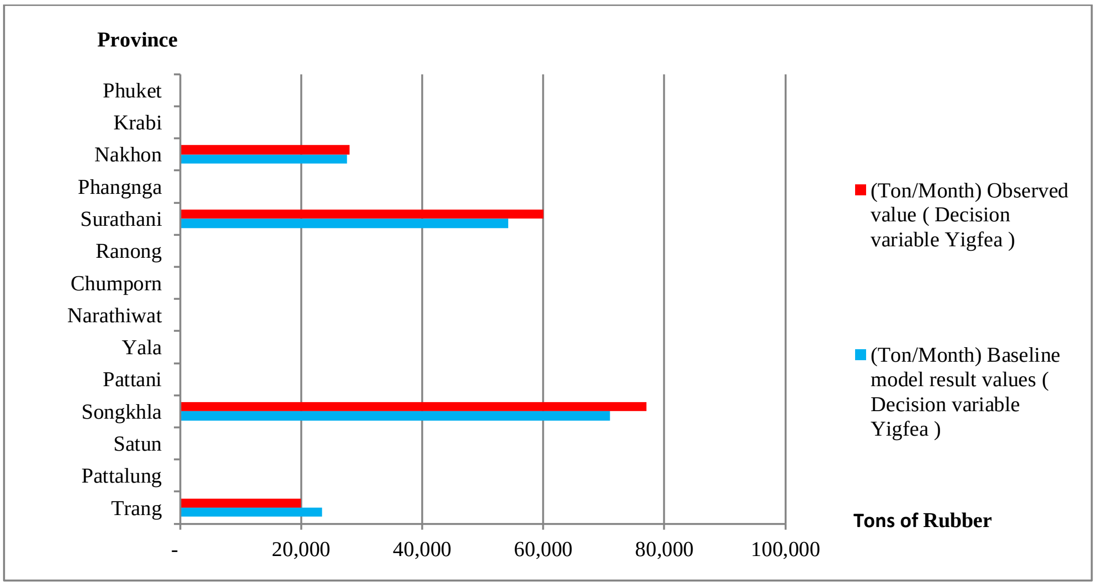

Figure 4-3: A comparison between the baseline model results and observed real world values for decision variable Y_{igfea}

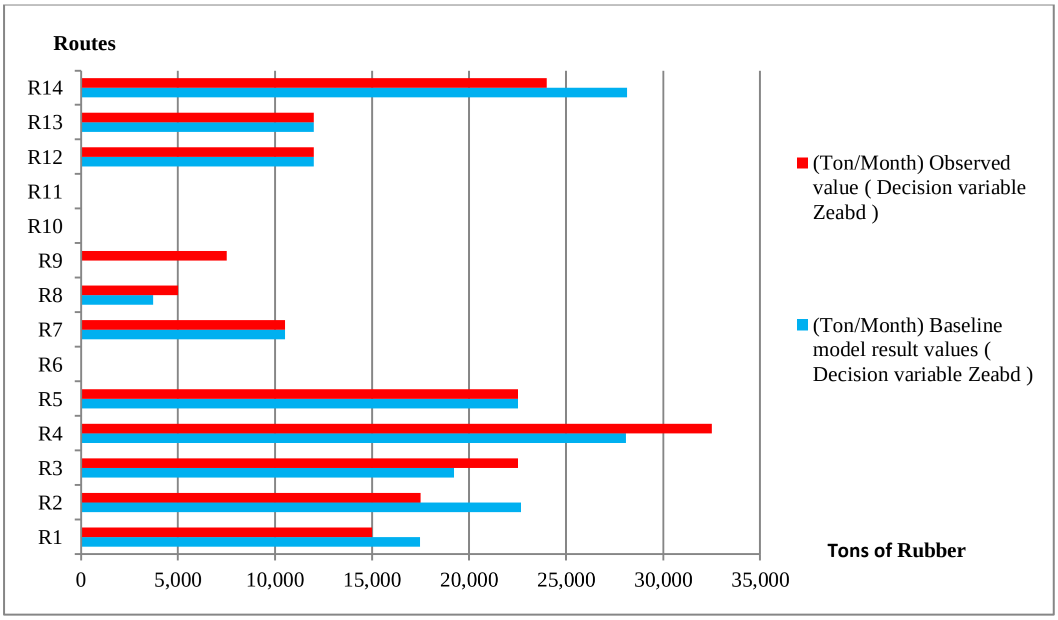

Figure 4-4: A comparison between baseline model results and observed real world values for decision variable Z_{eabd}

It can be seen from the above graph that the set of values matched each other fairly well, with marginal deviations for variable X_{isptg} and Y_{igfea}. For variable X_{isptg} (the primary rubber product produced from farmer) and Y_{igfea} (the intermediate rubber product produced from factory), the marginal deviation can happen since rubber is a commodity product which has many factors affecting the production, including weather, future market activities and supply and demand (AFET 2012). However, for variable Z_{eabd}, transportation route R9 showed a 100% deviation from the baseline model results in comparison with observed real world values. Transportation route R9 is the direct transport road to Laemchabang port. The strong deviation can be explained by the fact that road freight claims the highest costs and emissions of transportation compared to other modes such as rail freight or short sea shipping (DEFRA 2012). Therefore, the model of minimising costs and GHG emissions did not allocate any shipments via this route, while in practice, exporters may not be aware of the cost disparity issue. Meanwhile, the other transportation routes values proved of relatively good-fit with each other.

Furthermore, it is important to note that although the validation results suggest that each decision variable in the model is not exactly representative of observed real world values, such deviations have been deemed acceptable representations of reality by a group of experts in the Thai Rubber industry. In addition, Ali, Choudhry and Lister (1997) support the view that rubber as a commodity crop has a high volatility with regard to cultivation and production due to several factors such as the weather and the supply and demand factors regarding future markets. Consequently, these results suggest that the model outputs are not significantly different from the situation in the field; the comparison therefore validated the model results as representative of real world values.

4.6 THE CURRENT THAI RUBBER SUPPLY CHAIN NETWORK FLOW

Prior to presenting the model results network flow of costs and GHG emission minimisation in the following section, this section outlines the current Thai Rubber supply chain network flow. It aims to provide the background to the situation in the field with regard to how the supply chain networks are managed. Figure 4-5 below depicts the current Thai Rubber supply chain network flow.

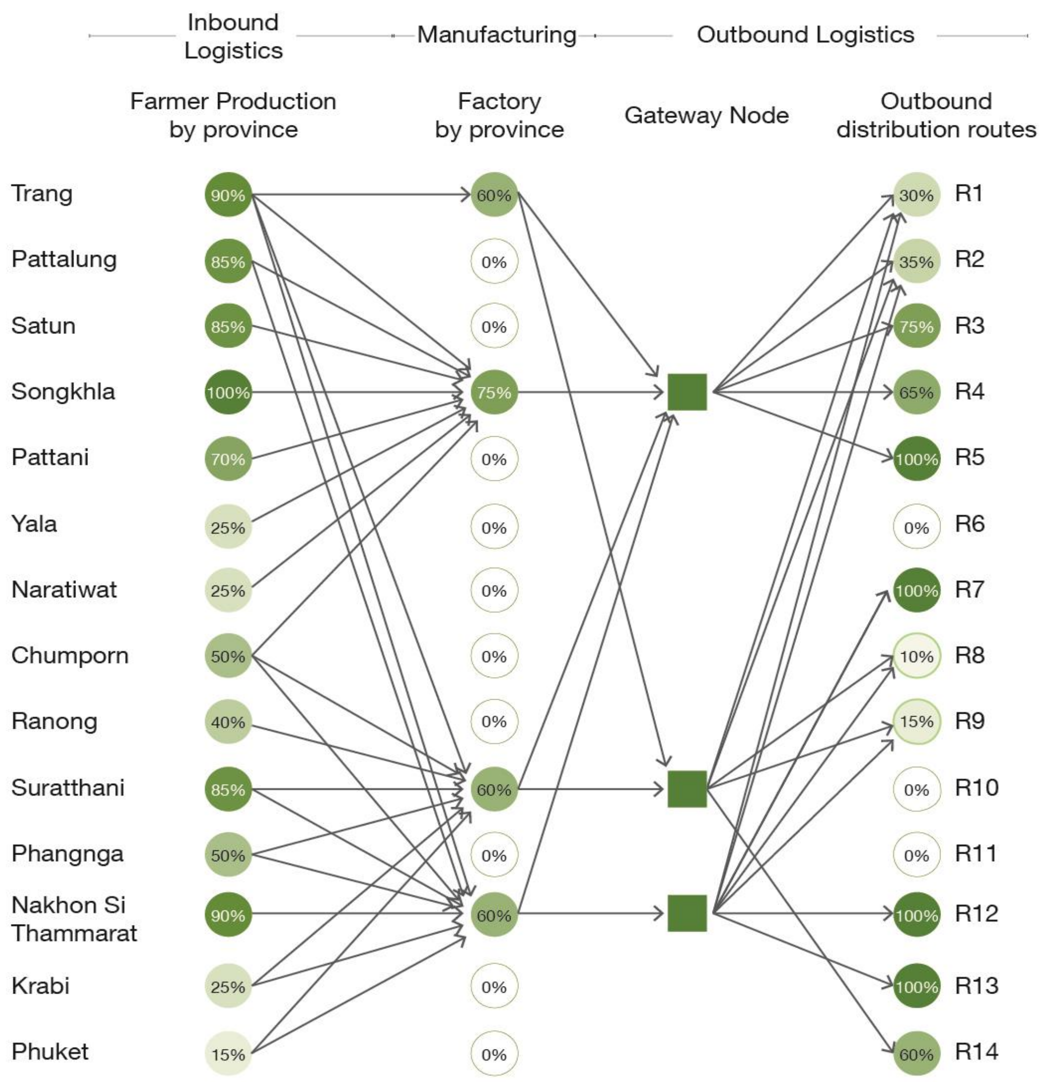

Figure 4-5: The current Thai Rubber supply chain network flow

The network flow above shows the flow associated with the capacity utilisation percentage of rubber products in each node. The flow moves from farmer to trader group to factory to gateway node, and then to destination by each transportation freight route. In the network flow presentation, farmer production node, factory node, gateway node and outbound distribution route nodes are used to describe the rubber supply chain network flow in the system. The trader group node is not presented in the optimal network flow. This is due to rubber trading activities taking place at the provincial level rather a regional level. Each node in farmer production and in the factory node represents the summation of each province's capacity (the 14 provinces in Southern Thailand). There are 14 nodes for outbound distribution transportation routes, representing transport routes R1 to R14. The colours and figures shown at each node signify the capacity utilisation percentage. The darker green shades indicate a higher percentage of capacity utilisation while the lighter green and white signify a lower percentage of capacity utilisation allocated by the model.

It can be seen that the network flows in current industrial practice do not show any regular pattern, in fact the pattern may be deemed chaotic. Farmer production has moved mainly to three provinces; Songkhla, Suratthani and Nakhon Si Thammarat. Only products from Trang are sent to manufacturers in the same province. After primary rubber products are processed into intermediate rubber products, they are delivered to their final destinations through gateway nodes in Songkhla, Suratthani and Nakhon Si Thammarat. The main outbound transportation routes from the gateway node at Songkhla are R1, R2, R3, R4 and R5. Routes R1, R2, R8, R9 and R14 are transportation routes from the Suratthani gateway node while R1, R2, R7, R8, R9, R12 and R13 are transportation routes from the Nakhon Si Thammarat gateway node.

In the next section, the model results for costs and GHG emission minimisation, along with the optimal network flow are presented and discussed.

4.7 MODEL RESULTS

The model was formulated, and problem solving carried out using the commercially available optimisation software ILOG CPLEX[7] version 12.3 (32-bit operating system, 2.33 GHz CPU, and 4.00 GB). All computational work was performed on a personal computer. The respective scope of the problem was defined by 4,789 variables subjected to 295 constraints. The optimisation results are presented as a network flow. Figures 4-6 and 4-7

[7] IBM Academic Initiative: CPLEX Optimiser

represent the cost minimisation and GHG emission minimisation optimal network flow. In addition, the results of cost minimisation (objective function 1) and GHG emission minimisation (objective function 2) for all decision variables are presented in Table A-26 to A-37 in the Appendix.

4.7.1 Cost minimisation results

The optimisation results show that the minimisation of costs comes to a total cost of 16,045 million Baht per month to supply 176,259 tons per month of intermediate rubber products to all destinations. This translates to a total cost of 91,083 Baht per ton. In addition, the correspondence GHG emissions for costs minimisation results is 199,550 tons of GHGs. Currently, the total cost of producing rubber products in the Thai Rubber industry is estimated at 92,530 Baht per ton (TRA 2012a). Compared with the optimisation solution, this is a reduction of 1,447 Baht per ton, which translates to approximately 1.56% in cost savings to the rubber industry. With the amount of rubber exports at 2.87 million tons per year, the savings total comes to 4,148 million Baht per year, or approximately USD138 million per year. It is worth mentioning that although these cost savings may seem relatively small to some industries, such cost savings are meaningful to both the Thai Rubber industry's private and public sector. The profit margin for rubber products is very small in general, being approximately 0.5% - 2% (TRA 2012a). Therefore, a cost saving of 1.56 % is seen as substantial for the Thai Rubber industry.

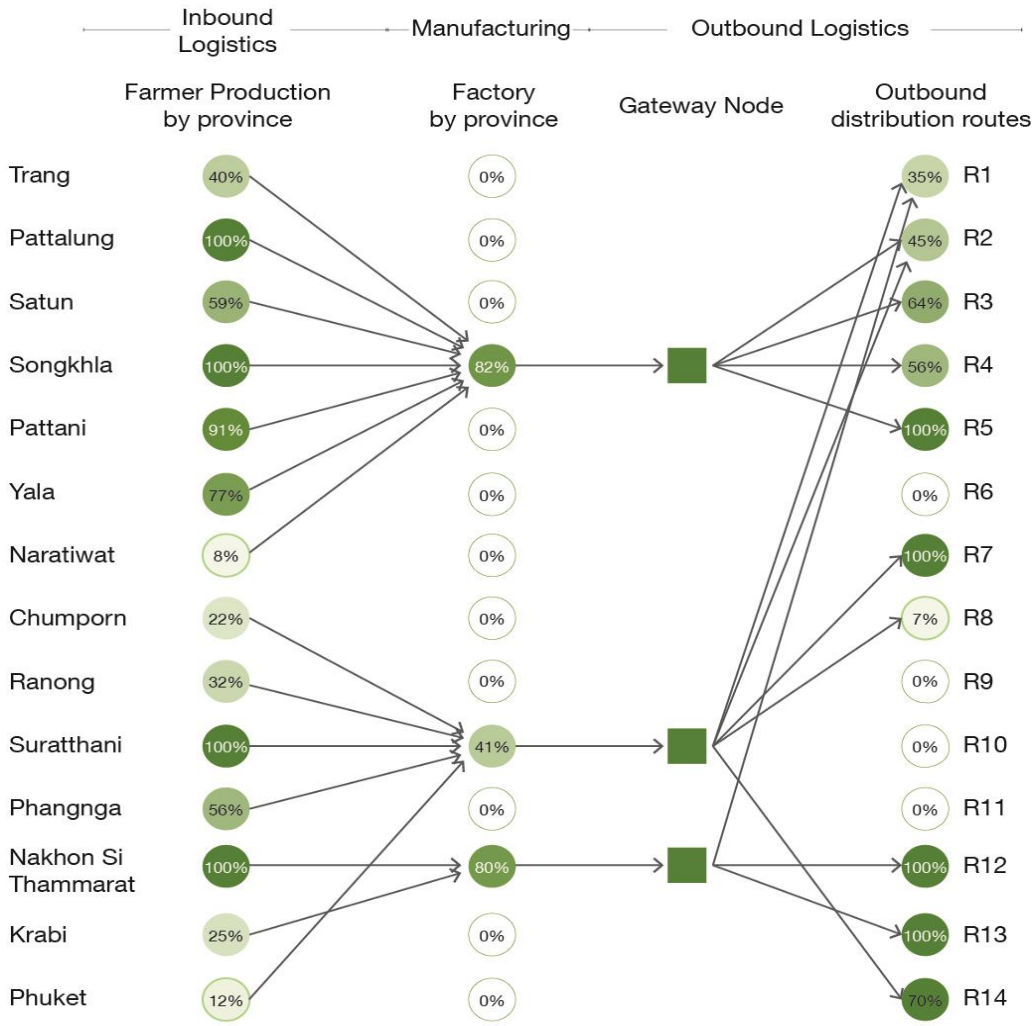

Figure 4-6: Costs minimisation optimal network flow

4.7.2 Greenhouse gas emission minimisation results

The results of GHG emissions minimisation (objective function 2) show that the optimal solution is to supply rubber products at a rate of 176,259 tons per month, which produces a total of 191,479 tons of GHGs and a total costs of 16,093 million Baht per month. This can be translated to 1.08 tons of GHG emissions per ton of product. To the best of the author's knowledge, this thesis is among one of the first investigations to calculate total GHG emissions from the Thai Rubber supply chain. Therefore, as yet, there are no available references for a results comparison.

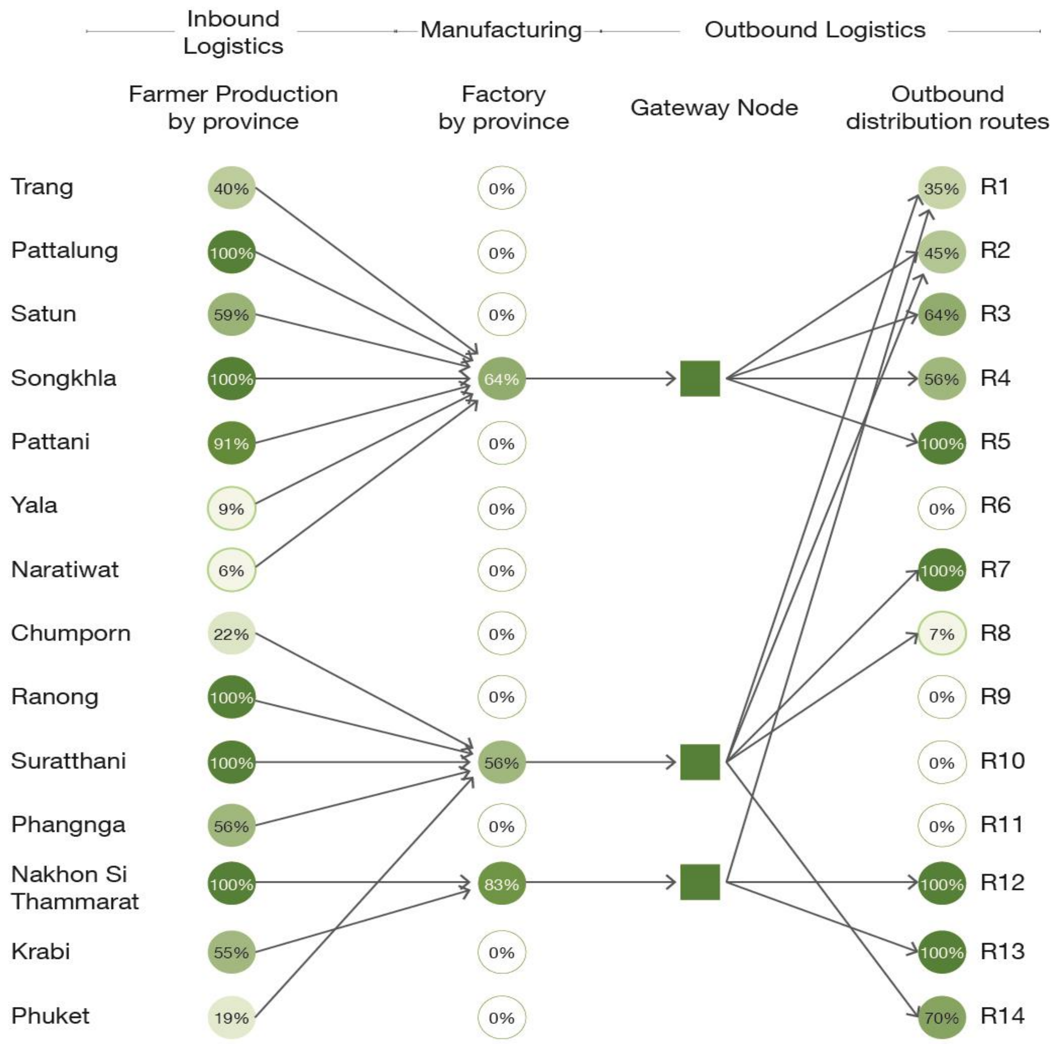

Figure 4.7: GHG emissions minimisation optimal network flow

4.7.3 The relationship between optimal costs and GHG emission minimisation results

The results of the costs and GHG emissions minimisation analysis shown in Figures 4-6 and 4-7, when compared to current industrial practice (Figure 4-5), clearly show that the model result network flow has a more effective order of organisation. This is due to the resulting model managing the optimal volume and the flow of the products. However, this chapter will not discuss the differences between these network flows in detail but will focus on examining the relationship between the optimal network flow of costs and GHG emissions minimisation.

The results of the costs and GHG emissions minimisation analysis shown in Figures 4-6 and 4-7 show the same optimal network flow pattern, while the differences between these two objective function optimal results are the percentages of capacity utilisation allocated to each node. The differences in capacity utilisation percentages include farmer production utilisation percentages and factory capacity utilisation percentages. Similar optimal costs and GHG emissions minimisation results were produced with regard to outbound distribution transportation route capacity utilisation percentage and network flow.

The comparison between optimal costs and GHG emission minimisation results is detailed below:

4.7.3.1 Farmer production: Inbound logistics

There are five provinces which were allocated different farmer production utilisation capacities, according to the costs and GHG emissions minimisation model. These were: Yala, Narathiwat, Ranong, Krabi and Phuket. Narathiwat and Phuket had slightly different percentage allocations with regard to farmer production. The model allocated 8% and 6% to Narathiwat for costs and GHG emissions minimisation respectively. Phuket's percentage of farmer production allocation toward minimising costs was 12% while GHG minimisation emissions accounted for 19%. While the model for GHG emissions minimisation allowed for 100% of farmer production capacity to be in Ranong, the model for cost minimisation allocated only 32%. Yala, on the other hand, was allocated higher percentages of farmer production utilisation from the costs minimisation model at 77%, but lower percentages from the GHG emissions minimisation model at 9%. Phangnga and Krabi were allocated 56% and 25% respectively from the cost minimisation model, and 56% and 55% respectively from the GHG emissions minimisation model. It can be seen that the gateway nodes and surrounding provinces have a higher percentage allocation compared to other provinces. It can therefore be suggested that the nearer it is to the gateway province, the higher the percentage for the province. Table 4-1 below presents farmer production utilisation capacities, according to the costs and GHG emissions minimisation model.

Table 4-1: Farmer production utilisation capacities: according to the costs and GHG emissions minimisation model

Province	Cost minimisation utilisation capacities	GHG emissions minimisation utilisation capacities
Trang	40%	40%
Pattalung	100%	100%
Satun	59%	59%
Songkhla	100%	100%
Pattani	91%	91%
Yala	77%	9%
Narathiwat	8%	6%
Chumporn	22%	22%
Ranong	32%	100%
Suratthani	100%	100%
Phangnga	56%	56%
Nakhon Si Thammarat	100%	100%
Krabi	25%	55%
Phuket	12%	19%

4.7.3.2 Factory production: Manufacturing

Factory capacity utilisation allocated by the model for cost minimisation was 82% to the factory in Songkhla, 41% to the factory in Suratthani and 80% to the factory in Nakhon Si Thammarat, while GHG emission minimisation allocated 64%, 56% and 83% to the factories in Songkhla, Suratthani and Nakhon Si Thammarat province respectively.

4.7.3.3 Outbound distribution routes: Outbound logistics

It can be seen that similar results from costs and GHG emissions minimisation are produced with regard to transportation freight route capacity utilisation. The model allocated 35% to R1, 45% to R2, 64% to R3, 56% to R4, 70% to R14, and 100% to R5, R12 and R13. However, the model did not allocate any capacity to R6, R9, R10 and R11. From the results, it can be seen that the model was prioritised to allocate volume to road-rail intermodal transport, which is the cheapest and lowest GHG emissions freight system in Thailand, compared to the road-short sea shipping transport system. Direct road transport is allocated to destinations that only have access to road freight, such as route R3 to Songkhla port, R1 to domestic stock and R2 to domestic consumption. For route R4 to Penang port, direct road transport was allocated due to the capacity limitation of road-rail intermodal transport from routes R5 and R7. The results show that routes R6, R10 and R11 have no capacity allocation even though these are road-rail intermodal transport systems. This is due to a bottleneck in rail service capacity from Hatyai to Padang Basar for train access to Penang port, and from Hatyai to Ladkrabang ICD for train access to Bangkok and Laemchabang port. This short-haul bottleneck capacity limits the long-haul route capacity. Route R9 direct road transport to Laemchabang port also has no capacity allocated. This is due to there being alternative routes which have sufficient capacity and are either cheaper or create less pollution, such as Routes R13 or R14.

Figure 4-8 shows the outbound transportation modes and routes of the cost and GHG emissions minimisation optimal network.

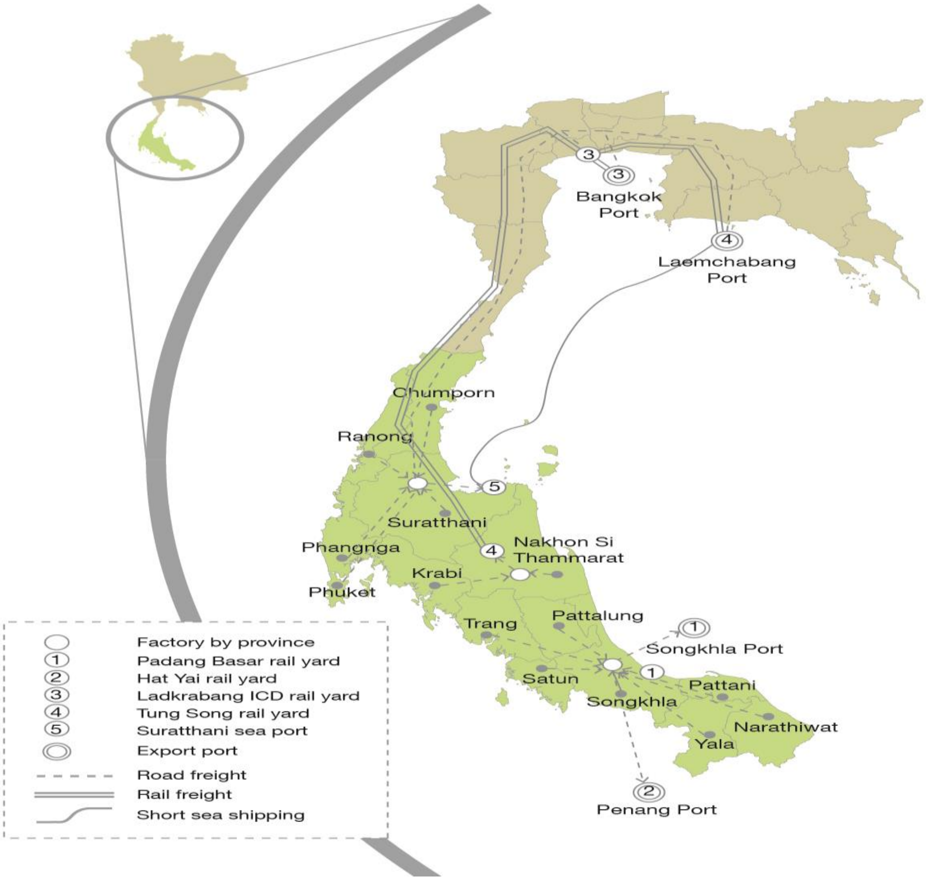

Figure 4-8: The outbound distribution transportation optimal network of costs and GHG emissions minimisation

4.8 SENSITIVITY ANALYSIS

In order to determine the impact of changes in parameter values in the model, a sensitivity analysis was performed. In this section, a sensitivity analysis was conducted to identify the impact on objective function values from changes in production and demand. A set of ten scenarios was created to represent different variations in production and demand (See Table A-47 in Appendix for each scenario value). These ten scenarios are the variation of production and demand which were a random volume measure taken from normal distribution with a mean equivalent to zero and a standard deviation equivalent to 10% of the value of the parameter.

The results from running each scenario were compared against the baseline model results to observe the changes in the value of the objective function. Figure 4-9 and Figure 4-10 depict the percentage of deviation between the baseline model results and the scenario model results in terms of changes in the objective function value for changes in production and demand.

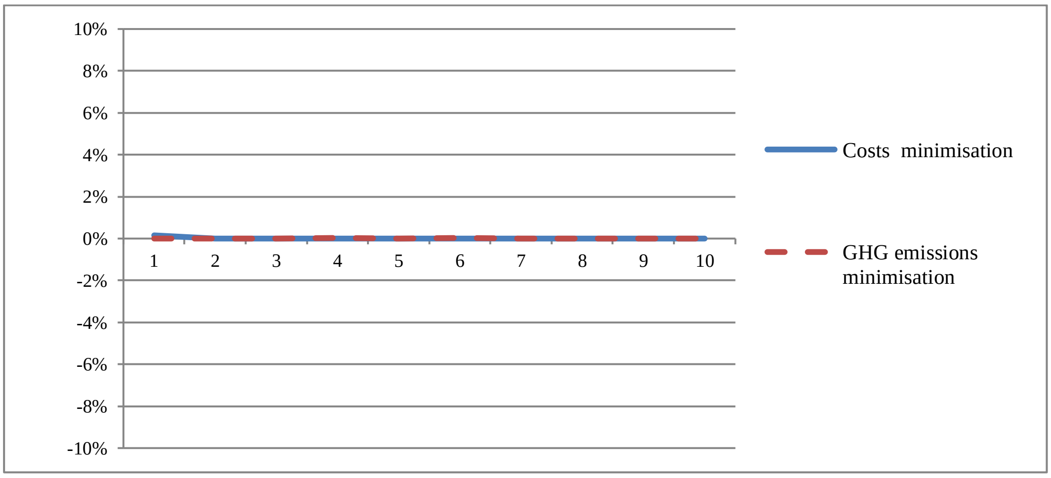

Figure 4-9: Percentage of deviation in terms of changes in objective function values when production changes (See Table A-48 in Appendix for each scenario's objective function value)

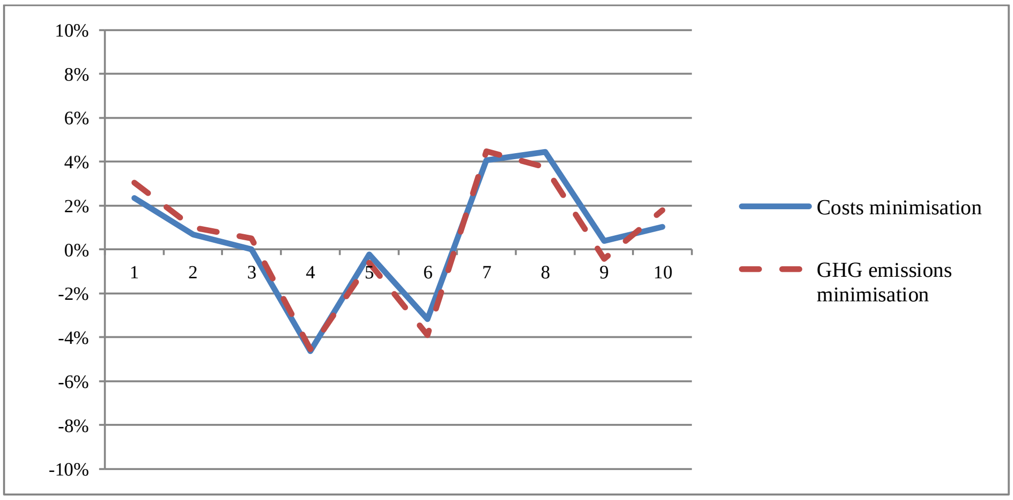

Figure 4-10: Percentage of deviation in terms of changes in objective function values when demand changes (See Table A-49 in Appendix for each scenario's objective function value)

In terms of impact on the objective function values for changes in production, a sensitivity analysis of results shows that the optimum costs minimisation and GHG emissions minimisation are not sensitive to changes in production. In Figure 4-9, the graph has only one visible line, as GHG emissions values are lying under the costs line. All scenarios (1 to 10) show a 0% deviation from the baseline model results. However, the optimum supply chain for costs and GHG emissions minimisation is more sensitive to changes in demand, as shown in Figure 4-10. It can be seen that the changes in demand result in changes in the objective function values of - 4.63% in scenario 4 and 4.43% in scenario 8 for cost minimisation. Similarly, for GHG emissions minimisation, in scenario 4 and 7, the changes are - 4.53% and 4.48% respectively. Therefore, the sensitivity analyses suggest that demand has more impact on the value of objective function than on production.

4.9 SUMMARY

In this chapter, a Green Supply Chain Management model for the Thai Rubber industry was developed. Its aim is to provide a decision support tool for policy makers to manage the Thai Rubber supply chain, in order to achieve economic gain while remaining environmentally friendly. Furthermore, this chapter also serves as the groundwork for a GSCM modelling framework and formulation for further investigation into the Thai Rubber supply chain in relation to costs and GHG emissions. This will be covered in later chapters.

The results from the model in this chapter indicate that by using the proposed model, the total cost of rubber production would be improved by 1.56% relative to current industrial practice. With regard to GHG emissions minimisation, this thesis is among one of the first investigations to calculate total GHG emissions from the Thai Rubber supply chain. It shows that the optimal GHG emissions minimisation is 1.08 tons of GHG emissions per ton of product.

An important insight gained from the model developed in this chapter is that farmer production and manufacturing process costs, and GHG emissions optimal results are incompatible. However, the results are compatible in the case of outbound distribution transportation. The implications are that if costs can be minimised in inbound logistics and manufacturing, it is not necessary to minimise total GHG emission. On the other hand, if costs in outbound logistics can be minimised, the total GHG emissions in this part of the supply chain can also be minimised. This then leads to the assumption that if outbound distribution modes such as rail bases and short sea shipping can be restructured to operate on lower transportation costs, total GHG emissions should be minimised as an additional benefit of cost reduction. Therefore, further investigation into the restructuring of outbound transportation could be undertaken to assess the impact on costs and GHG emissions in the Thai Rubber supply chain.

In addition to the insights gained from the model, it can also be seen that the Thai Rubber supply chain network flow is limited to three gateway nodes (Songkhla, Suratthani, and Nakhon Si Thammarat), as found in the field. From a model development perspective, these three gateway nodes seem to inhibit the model's capability when solving the problems of costs and GHG emissions minimisation. For this reason, the question is asked: If any of the fourteen provinces in the Thai Rubber supply chain could be selected from the model to be gateway nodes, which provinces should the model select? In this case, further investigation into the number of gateway nodes would provide new information to support decision-making in the restructuring of an optimal distribution network.

The results of the insights obtained, and observations made from this chapter point towards a further investigation into outbound logistics transportation and distribution restructure. The next chapter will address these questions.

CHAPTER 5

TRANSPORTATION AND DISTRIBUTION RESTRUCTURE IMPACT ON COSTS AND GREENHOUSE GAS EMISSIONS

5.1 INTRODUCTION

It is generally accepted in the existing literature on the rubber supply chain that effective transportation and distribution are vital to the supply chain. These activities contribute to both total logistic costs and environmental pollution (Winebrake et al. 2008; Kim, Janic and Wee van 2010; McKinnon 2010; Wang, Lai and Shi 2011). Albright and Lo (2009) also describe the transportation and distribution role as the most important method in achieving supply chain excellence in terms of the economy and the environment. However, there is a some disagreement in the literature regarding the impact of transportation and distribution restructuring on costs and the environment (Kohn 2005; le Blanc et al. 2006; Aronsson and Brodin 2006; Kohn and Brodin 2008; Harris et al. 2011).

Some of the literature has examined the impact of transportation and distribution restructuring in the supply chain network on costs and the environment in different industries. Le Blance et al. (2006) quantified the benefit of Factory Gate Pricing (FGP) for Dutch retail distribution. Their study found that FGP was of benefit in terms of reductions in both costs and environmental impact. Furthermore, Aronsson and Huge Brodin (2006) investigated three case studies in different industries with different distribution structures. They found that all changes in distribution systems led to positive environmental effects and lower costs. Nevertheless, not all transportation and distribution restructuring results in positive change in terms of the environment. Kohn (2005) points out that changing manufacturer distribution systems for submersible pumps and mixers from decentralised to centralised systems results in a positive impact on costs and service levels, but has a negative impact on the environment.

In addition, Harris et al.(2011) developed a costs- based optimisation model for infrastructure design to examine the relationship between total logistics costs and environmental impact. Their work focused on a number of depots along with freight utilisation ratios. The results showed that the optimum solution based on costs does not necessary equal the optimum solution based on environmental impact.

Even though the results of cost and GHG emission minimisation in Chapter 4 suggest that reducing outbound transport costs benefits the environment, the above reviews found that this is not always the case when transportation and distribution have been restructured. Thus, further analysis of the impact on costs and GHG emissions is required. In addition, an examination of the relationship between these two objective functions, after transportation and distribution restructuring, should provide new insights for policy makers in the Thai Rubber industry. The analysis in this chapter aims to support the Thai Rubber industry policy maker with decisions regarding the development of the transportation and distribution infrastructure. Analysis of, and improvements to network and service capacity should reduce costs and benefit the environment.

In this chapter, the findings from Chapter 4 will be expanded upon to examine the relationship between costs and GHG emissions in outbound distribution transportation. In addition, the impact of transport and distribution restructuring on costs and GHG emissions will be explored. The framework of assessment in this chapter is divided into two parts:

- The first part examines the impact of transportation service capacity on rail freight and short-sea shipping. These two modes of transportation are accepted as the soundest with regard to being economical and environmentally friendly (DEFRA 2004; IMO 2009). A scenario analysis related to different rail freight and short-sea shipping service capacities will be conducted to observe any changes in costs and GHG emissions. Any impact will be expressed as changes in the total costs and total GHG emissions, using the baseline model results as a benchmark. Total costs will be measured in terms of Baht per ton of rubber product, while GHG emissions will be measured in terms of tons of GHG emissions per ton of rubber product.

- The second part of the chapter aims to examine the impact of the restructuring of the distribution network on cost and GHG emission minimisation. In this analysis, the model developed in Chapter 4 will be utilised by changing the gateway node set from three to fourteen to represent the fourteen provinces. A scenario analysis will then be conducted, based on the cost and GHG emissions minimisation results. The scenario analysis results will then be compared with the baseline model results to evaluate any improvements in cost and GHG emission minimisation.

The chapter ends by detailing information to support industry policy makers in Thailand. It also presents findings from the research on the Thai Rubber supply chain literature and evaluates the design of the supply chain network restructure.

5.2 MATHEMATICAL FORMULATION

In this chapter, similar sets, parameters, decision variables, objective functions and constraints to those developed in Chapter 4 are utilised. These include objective function 1 for cost minimisation, objective function 2 for GHG emission minimisation, and constraints 3 to 16 for model constraints. The model data, parameters and variables are summarised in Appendix A. From the findings in Chapter 4, changes have been made to the models as follows:

- Freight route service capacity (FRC_b) for road-rail intermodal transport route R5, R6, R7, R10, R11, R12, and R13 was increased by 25%, 50%, 75% and 100%, and the short-sea shipping service capacity in route R14 was increased by 25% for the analysis in scenarios 9. The analysis of these scenarios will be performed in section 5.3.

- Cost parameters (CT_{ab}) for road-sea shipping route R14 were decreased by 25%, 50%, 75%, and 100% for the analysis in scenarios 5, 6, 7 and 8 respectively. The results of the scenario analyses will be discussed in section 5.3.
- Gateway node set ($a \in A$) was changed from three gateway nodes (Songkhla, Suratthani, and Nakhon Si Thammarat) to fourteen gateway nodes. These represent the fourteen provinces in Southern Thailand. The results of solving objective function 1 for cost minimisation and objective function 2 for GHG emission minimisation with fourteen gateway nodes will be discussed in section 5.4.

5.3 THE IMPACT OF OUTBOUND DISTRIBUTION TRANSPORTATION RESTRUCTURING ON COSTS AND GHG EMISSIONS

Rail freight and short-sea shipping is broadly regarded as an economical and environmentally friendly mode of transport among the four commonly used modes of transportation: road, rail, sea, and air (Winebrake et al. 2008; Kim, Janic and Wee van 2010). Moreover, earlier research into the Thai Rubber supply chain highlighted the importance of these two modes of transport in the development of the Thai Rubber industry. Wasusri and Chaichompoo (2008) came to two conclusions regarding the improvement of the Thai Rubber supply chain network transportation infrastructure: 1) Rail freight must be urgently prioritised in order to reduce logistics costs; and 2) Policy makers should promote short-sea shipping lines as an alternative to road freight.

In order to examine the impact of the development of outbound distribution transportation, nine different scenarios relating to road-rail intermodal transport and road-sea intermodal transport service capacity were explored. The nine scenarios are explained as follows:

- Scenarios 1 to 4 attempt to examine the impact on costs and GHG emissions when the rail freight service capacity of routes R5, R6, R7, R10, R11, R12, and R13 is increased by 25%, 50%, 75% and 100%. With regard to the current rail freight service capacity, it cannot be increased by 75% or 100% due to rail track constraints and congestion. A capacity increase of 25% to 50% is a more realistic proposal (State Railway of Thailand 2011) but the increase cannot be implemented in the near future without further infrastructure development. Despite the above factors it is still worthwhile to make projections regarding the higher capacities of 75% and 100% with a view to future developments.
- Scenarios 5 to 8 aim to investigate the impact of road-sea intermodal transportation route R14 on cost alone. These scenarios have been designed based on insights given by rubber exporters during interviews. One theme common to the interviews was that short-sea shipping prices are not competitive compared to other modes of transportation. Therefore, scenarios 5 to 8 aim to investigate the impact on cost minimisation when short-sea shipping prices are decreased by 10%, 15%, 20% and 25% of the current market price. Shipping companies have confirmed that a 25% price reduction is the maximum possible if government support is also given in terms of tax relief and expenses. Hence, 25% is the benchmark in the scenario criteria.
- Scenario 9 aims to analyse the impact on costs and GHG emissions when the short-sea shipping service capacity of route R14 is increased by 25% and prices are lowered by 25%. This scenario investigates the impact of

the optimum scenarios for short-sea shipping on service capacity and costs.

The baseline scenario is the optimal result of resolving the issues of costs and GHG emissions, as presented in Chapter 4. This scenario is used as the benchmark for comparison with the other scenarios. Tables 5-1 and 5-2 show the optimal results of each scenario and the percentages of each scenario's optimal costs and optimal GHG emissions minimisation compared to the baseline scenario.

Table 5-1: Scenario analysis results from solving objective function 1

Scenario		Optimal costs minimization (Unit : Baht)	The percentage of changes from baseline scenario
Baseline		16,045,402,681	
1	Increase rail freight service capacity by 25% (Route R5,R6,R7,R10,R11,R12,R13)	16,041,320,056	-0.03%
2	Increase rail freight service capacity by 50% (Route R5,R6,R7,R10,R11,R12,R13)	16,039,175,164	-0.04%
3	Increase rail freight service capacity by 75% (Route R5,R6,R7,R10,R11,R12,R13)	16,038,054,994	-0.05%
4	Increase rail freight service capacity by 100% (Route R5,R6,R7,R10,R11,R12,R13)	16,037,129,659	-0.05%
5	Decrease price of short sea shipping (Route R14) by 10%	16,031,338,256	-0.09%
6	Decrease price of short-sea shipping (Route R14) by 15%	16,023,458,256	-0.14%
7	Decrease price of short-sea shipping (Route R14) by 20%	16,015,538,256	-0.19%
8	Decrease price of short-sea shipping (Route R14) by 25%	16,007,538,256	-0.24%
9	Decrease price of short-sea shipping (Route R14) by 25% and increase short- sea shipping service capacity by 25%	16,007,425,786	-0.24%

Table 5-2: Scenario analysis results from solving objective function 2

Scenario		Optimal GHG emissions minimisation (Unit : Ton)	The percentage of changes from baseline scenario
Baseline		191,479	
1	Increase rail freight service capacity by 25% (Route R5,R6,R7,R10,R11,R12,R13)	185,649	-3.04%
2	Increase rail freight service capacity by 50% (Route R5,R6,R7,R10,R11,R12,R13)	183,868	-3.97%
3	Increase rail freight service capacity by 75% (Route R5,R6,R7,R10,R11,R12,R13)	182,208	-4.84%
4	Increase rail freight service capacity by 100% (Route R5,R6,R7,R10,R11,R12,R13)	180,956	-5.50%
5	Decrease price of short-sea shipping (R14) by 10%	191,479	0.00%
6	Decrease price of short sea shipping (Route R14) by 15%	191,479	0.00%
7	Decrease price of short-sea shipping (Route R14) by 20%	191,479	0.00%
8	Decrease price of short-sea shipping (Route R14) by 25%	191,479	0.00%
9	Decrease price of short-sea shipping (Route R14) by 25% and increase short-sea shipping service capacity by 25%	191,479	0.00%

The scenario analysis results from fulfilling objective function 1 for cost minimisation reveals that increasing the rail freight service capacity from 25% to 100% has a minimal impact on cost minimisation. Scenarios 1 to 4 in Table 5-1 show the cost reductions of 0.03%, 0.04%, 0.04% and 0.05% obtained by increasing rail freight service capacity by 25%, 50%, 75% and 100% respectively. Scenarios 5 to 8 regarding short-sea shipping price reductions show a slightly higher impact on optimal cost minimisation. The short-sea shipping price reduction of 25% in scenario 8 results in a 0.24% cost saving against the baseline model results. Scenario 9 for the short-sea shipping price reduction of 25% and a service capacity increase of 25% also results in the same optimal cost minimisation as that found in scenario 8. The reduced short-sea shipping price has a greater impact on cost reduction than the increase in rail freight service capacity. However, both are considered to have a low impact on optimal cost minimisation as the percentage of each scenario when compared to the baseline model results is less than 0.3%.

On the other hand, the analysis of the impact on GHG emissions shows that an increase in rail freight service capacity results in a notable reduction of GHG emissions, as shown in scenarios 1 to 4 in Table 5-2. Scenarios 1 to 4 indicate the reduction in GHG emissions by 3.04%, 3.97%, 4.84% and 5.50%, with the increase in rail freight service capacity by 25%, 50%, 75% and 100% respectively. The decrease in GHG emissions is not surprising, given that rail freight is considered one of the most environmentally friendly modes of transportation.

The relatively low impact on costs saving from increases in rail freight service capacity may seem surprising. Since rail freight is considered to be the cheapest mode of transport, increasing its service capacity should reduce overall costs. However, trains are not used for the whole of each service leg. The rail freight intermodal terminals are located in three provinces: Songkhla, Suratthani, Nakhon Si Thammarat. On each route, the pre-haulage and post-haulage legs are operated by truck. Therefore, altering the rail leg service cannot have a direct impact upon the lowering of overall costs due to the necessity of using trucks. In addition, when the pre-haulage distance is longer than the rail leg, taking an alternative route using direct road or short-sea shipping may be more cost-competitive. Furthermore, with regard to GHG emissions, when comparing the cost per unit for the same distance travelled by rail freight to other modes of transportation, costs decrease at a lower proportion than GHG emissions. Hence, all these elements in rail freight service capacity impact upon both costs and GHG emissions in the same way but in different proportions.

For short-sea shipping, it can be seen that increasing service capacity by 25% has no impact on optimal GHG emission minimisation. Scenario 9 shows 0% changes in optimal GHG emission minimisation compared to the baseline scenario model results. In terms of short-sea shipping, the benefit to the environment is somewhat ambiguous. Although some of the literature and certain government agencies deem short-sea shipping to be a 'green' mode of transportation (IMO 2009; Kim, Janic and Wee van 2010), Hjelle and Fridell (2012) argue that it is not always true that short-sea shipping is more environmentally friendly than other modes of transport. The authors point out that short-sea shipping is more environmentally 'competitive' with regard to vessels transporting bulk commodities such as iron ore, oil, or chemicals but this is not necessarily the case for general cargo, container or RORO[8] vessels. These types of cargo vessels are generally designed to travel to and from deep sea destinations, or are used for partial transport within the continent. As such, the environmental performance of this type of cargo vessel is different from that of the bulk cargo vessel. Four major disadvantages to environmental performance are payload, speed, shipment size and the double-load factor. All these factors contribute significantly to the lowering of fuel efficiency and, ultimately, environmental performance (Hjelle and Fridell 2012). Hence, this evidence supports the results of scenario 9 where increasing the capacity of route R14 for short- sea shipping produces little effect upon GHG emission minimisation.

In summary, it can be observed that the impact on cost minimisation from the increase in rail freight service capacity is marginal, while the impact on GHG emission

[8] RORO vessel is an abbreviation for Roll on/Roll off vessel. It is designed with ramps that can be lowered to the dock so trucks or other vehicles can drive into the ship (APPA,2013)

minimisation is more significant. In terms of short-sea shipping prices and service capacity, the scenario analysis shows a slight positive impact on cost minimisation but no positive or negative impact on GHG emission minimisation.

It can be seen from the above analysis that rail freight and short-sea shipping are not competitive enough as economic strategies. This therefore does not support the claims made by Wasusri and Chaichompoo (2008) and some of the earlier research into the Thai Rubber supply chain (Kritchanchai 2009) that rail freight and short-sea shipping are economically competitive strategies. The methodology proposed in this thesis utilised an optimisation tool which obtained the best possible solution while the earlier research in this area performed a simple scenario analysis. In this sense result of this research is the optimal one.

The findings in this section have provided new insights for policy makers in the Thai Rubber industry, for example the development of outbound distribution transportation for rail freight and short-sea shipping will not result in worthwhile economic benefits. The comparison between scenarios 1 to 4 and scenarios 5 to 8 suggested that reducing short-sea shipping prices would provide more benefit to the rubber industry than investment in rail freight infrastructure. However, from an environmental point of view, the development in rail freight service capacity would provide greater environmental benefits to the rubber industry.

5.4 THE IMPACT OF DISTRIBUTION RESTRUCTURE ON COSTS AND GREENHOUSE GAS EMISSIONS

In the Thai Rubber industry, the main rubber activities and export gateways are in the provinces where the general market is also located. Initially, the Thai Government found the general marketplace to be the auction centre for rubber products (OAE 2007). However, the role of the general marketplace has now expanded to cover all rubber activities such as trading, marketing and distribution. The number of rubber plantations and manufacturers in the provinces and surrounding areas has rapidly increased. Development of intermodal terminals handling regional cargoes serving major exporting ports in Thailand and surrounding areas has also expanded. As mentioned in the previous chapter, there are currently three general markets in Southern Thailand, located in the provinces of Songkhla, Suratthani, and Nakhon Si Thammarat. In this thesis, the three provinces are termed gateway nodes, as can be seen in Figure 5-1.

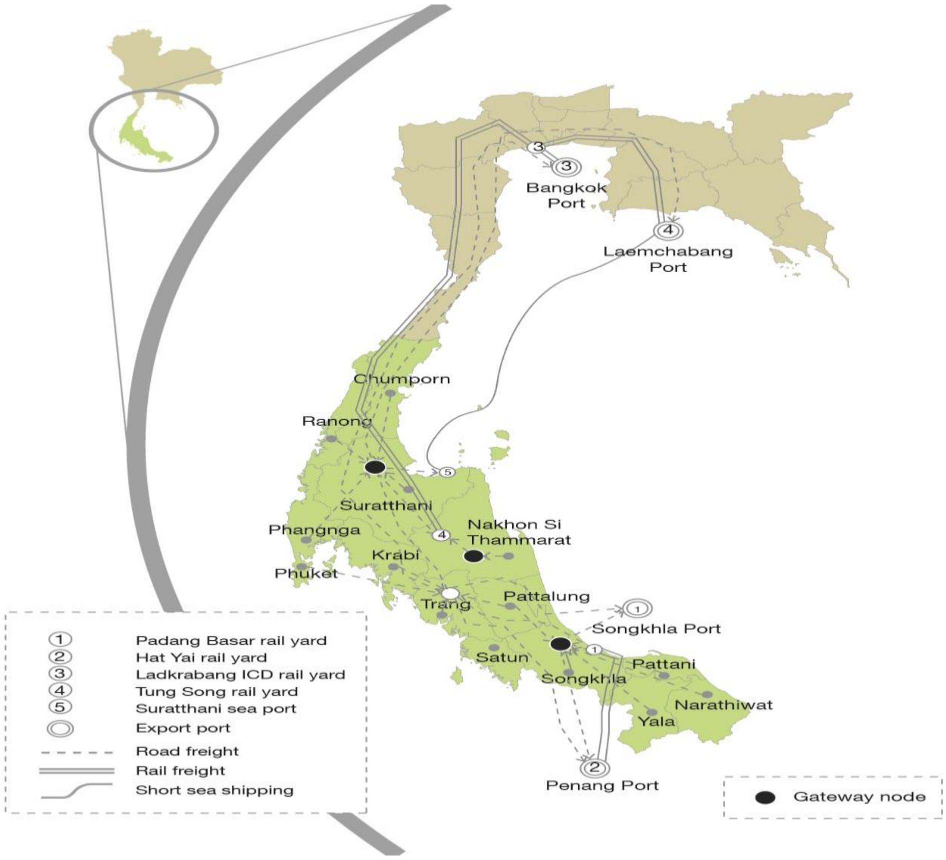

Figure 5-1: The location of three gateway nodes in the study area

Chapter 4 explored the optimal results of cost and GHG emission minimisation based on current industrial practice and exploring three gateway nodes. However, from the model development perspective, these three gateway nodes seem to inhibit the model's capability when allocating volume to each supply chain entity in the network. For this reason, the question is asked: if the model is developed to examine fourteen provinces from which gateway node selections will be made, which provinces will be selected from the model?

To answer the above question, the model developed in chapter 4 will be adopted and modified to solve the cost problem (objective function 1) and the GHG emission problem (objective function 2) by changing the set of gateway nodes to fourteen. Subsequently, the results will be discussed and analysed. Following this, an examination of the impact of the distribution restructure will be undertaken by scenario analysis using the new results of cost and GHG emission minimisation from this current chapter. The focus in this section is to examine whether the distribution network restructure, based on the new cost and GHG emission results, has an impact upon costs and GHG emissions.

According to McKinnon (1998), a distribution network is composed of number, location and choice of distribution channels. Any changes made to this configuration are highly likely to influence the total cost and the environmental impact on the supply chain (Hugo and Pistikopoulos 2005; Aronsson and Brodin 2006). In the analysis of this section, the configuration of the distribution network is referred to by number and location of gateway node. The choices of distribution channels are the manufacturing and outbound distribution links, which are represented by the fourteen outbound distribution transportation routes.

The following section presents the results of cost minimisation (objective function 1) and GHG emission minimisation (objective function 2) after changing the set of gateway nodes from three to fourteen.

5.4.1 Cost minimisation results

The network flow of the solution to objective function 1 for cost minimisation is depicted in Figure 5-2. This network produces a total cost of 15,876 million Baht per month, which corresponds to produce a total of 190,787 tons of GHGs. The results of costs minimisation identified an optimum number of four gateway nodes made up of: Songkhla, Suratthani, Nakhon Si Thammarat and Trang. It can be seen that Trang has been added to the three original nodes to become the fourth gateway node.

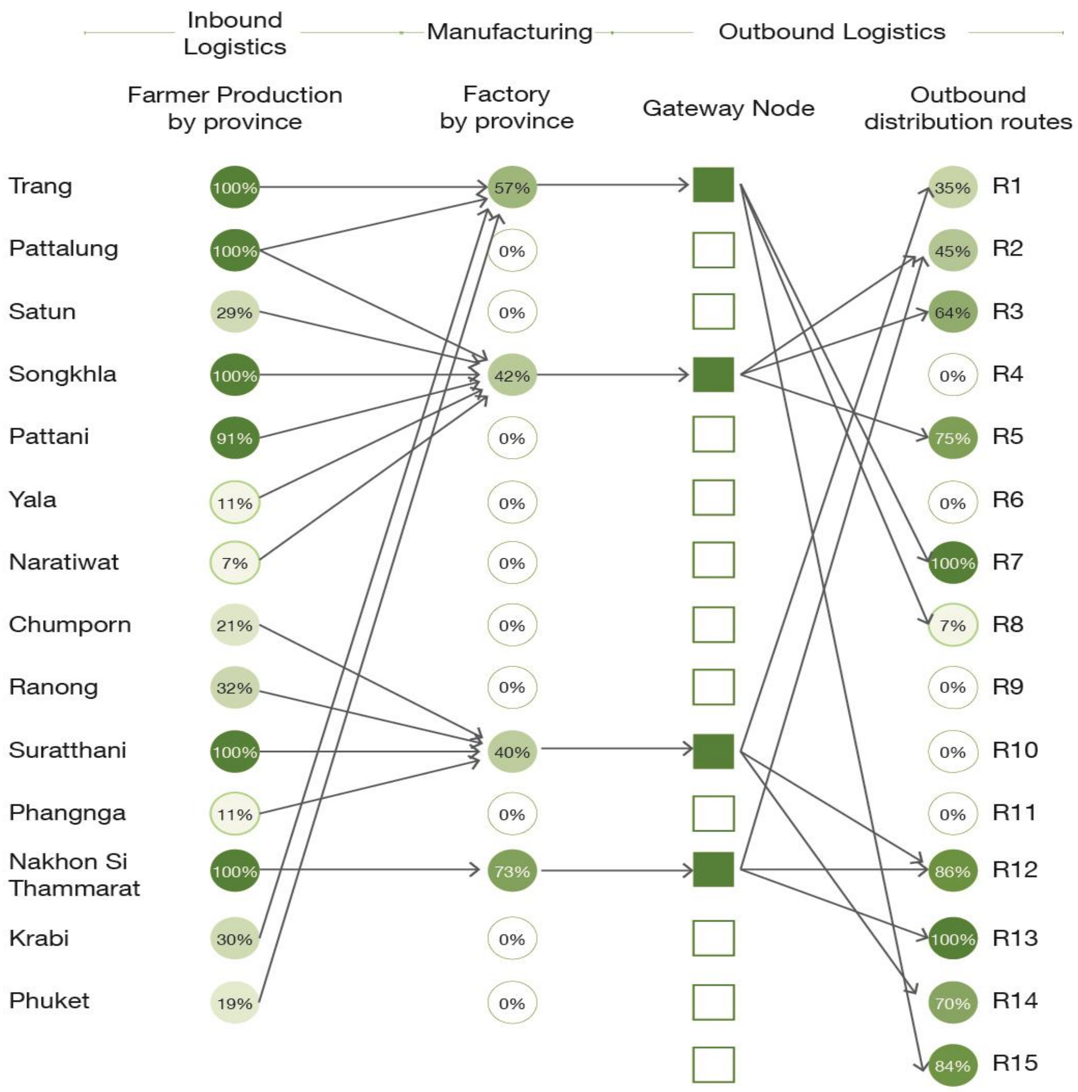

Figure 5-2: The optimal network flow solution to objective function 1 for cost minimisation

5.4.2 GHG emission minimisation results

The network flow solution to objective function 2 for GHG emission minimisation is presented below in Figure 5-3.

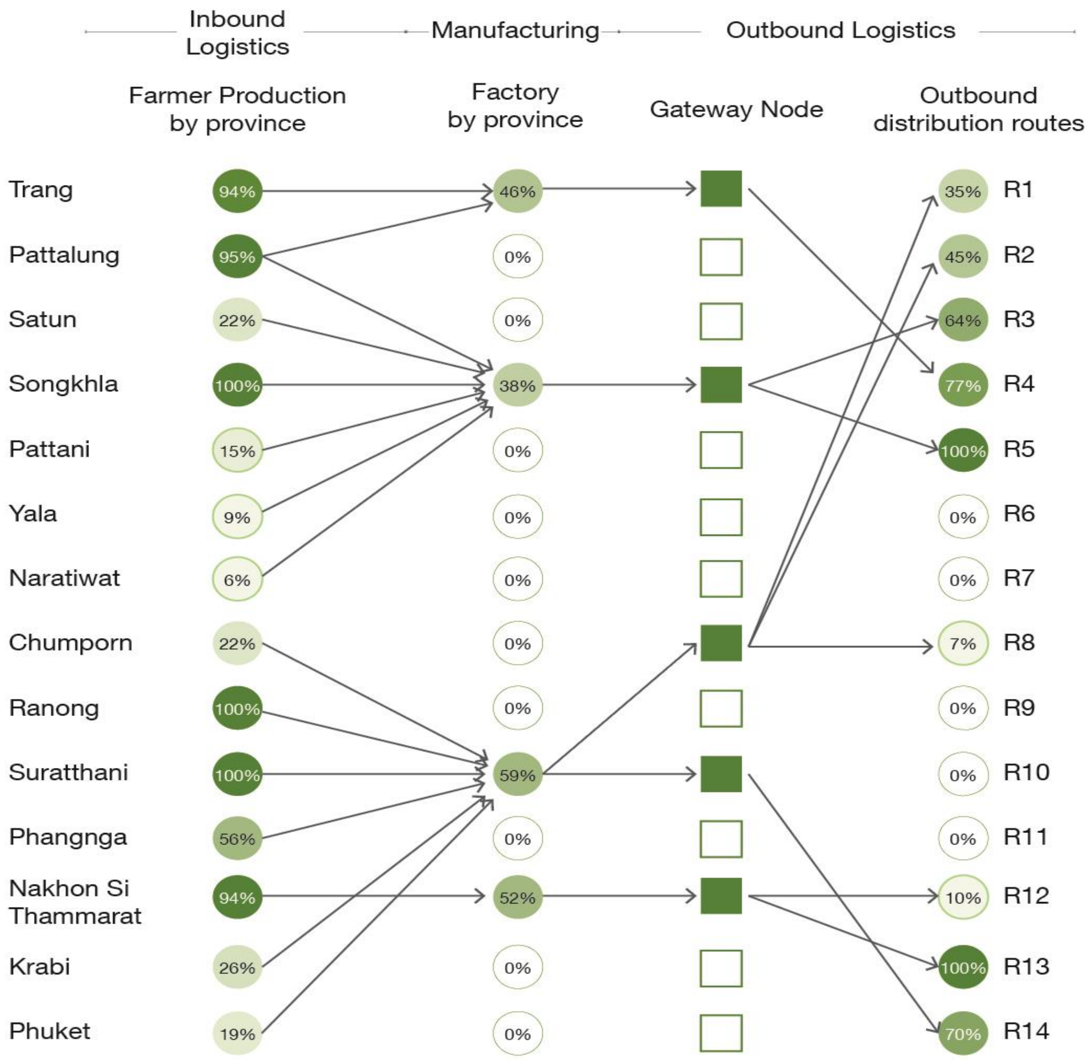

Figure 5-3: The optimal network flow solution to objective function 2 for GHG emission minimisation

For GHG emission minimisation results, five provinces were chosen after running the modified model. These were: Songkhla, Suratthani, Nakhon Si Thammarat, Trang and Chumporn. Two additional provinces, Trang and Chumporn, were also chosen. Furthermore, this network produces a total of 188,375 tons of GHG emissions and the corresponding costs of 15,889 million Baht per month.

5.4.3 Optimal gateway node location from modified model

Figure 5-4 represents an overview of the optimal network configuration, using the costs and GHG emission minimisation results from the modified model in this chapter and those from the baseline model in Chapter 4. For cost minimisation, the optimum number of gateway nodes is four, with five gateway nodes being selected for GHG emission minimisation. As can be seen, Trang province was added as the fourth gateway node for cost minimisation while Trang and Chumporn were chosen for GHG emission minimisation after examining the baseline model results for Songkhla, Suratthani, and Nakhon Si Thammarat.

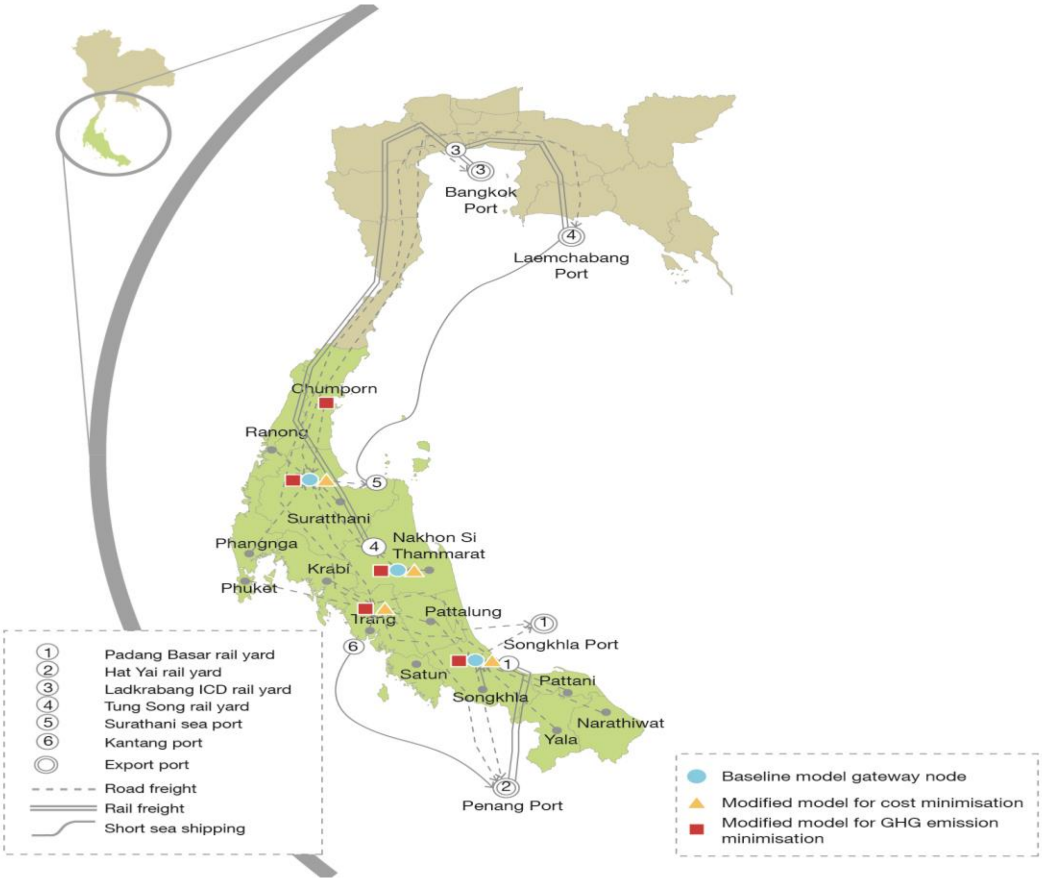

Figure 5-4 Optimum gateway node locations

5.4.4 Scenario analysis of distribution restructuring based on costs and GHG emission minimisation optimal network configuration.

In this section, four different scenario analyses were performed, based on the optimal results of cost and GHG emission minimisation from the previous section. It can be seen from the previous section that the configurations of the distribution network of these two objective functions are different. Thus, the focus in this section is on the scenario analysis, based on the two models' optimal distribution networks at four and five gateway nodes respectively.

The objective of this section is to explore the impact on costs and GHG emissions compared to the baseline scenario. The baseline scenario, as indicated in section 5.3, is the optimal result of cost minimisation and GHG emission minimisation for current industrial practice with three gateway nodes, as presented in Chapter 4.

The description of the four scenarios is explained below:

- Scenario 1 is the modified model of the optimal solution to minimising costs (see section 5.4.1). It aims to examine the impact of distribution network restructuring based on costs from the four chosen gateway nodes (Songkhla, Suratthani, Nakhon Si Thammarat, Trang). The impact is demonstrated in terms of any lowering of costs and GHG emissions, as compared to the baseline model results.
- Scenario 2 is the modified model of the optimal solution to the lowering of GHG emissions (see section 5.4.2). It aims to examine the impact of distribution network restructuring, based on GHG emissions with regard to the five chosen gateway nodes (Songkhla, Suratthani, Nakhon Si Thammarat, Trang, Chumporn). The impact is demonstrated in terms of lowering of costs and GHG emissions, as compared to the baseline model results.

- Scenarios 3 and 4 focus on assessing the impact of distribution network restructuring, based on the optimum network for costs and GHG emissions at four and five gateway nodes respectively, with the addition of the new transport route R15. This route is made up of road-sea intermodal transport. For this route, cargo is transported by truck, from its origin to the Kantang coast's port terminal before being moved by short-sea shipping to Penang port. This scenario was designed according to the government's sustainable transport development roadmap. This develops the western corridor for short-sea shipping which connects to major exporting ports in Malaysia (MOT 2007). This route is therefore seen as a potential development route for the rubber industry's outbound distribution network. Since Kantang port is located in Trang province, the development of new route R15 accords with the optimal cost and GHG emission results in this chapter, with Trang province as the fourth gateway node. Consequently, this scenario provides new insight for policy makers to evaluate the feasibility of developing Kantang port as the western short-sea shipping corridor for the rubber industry.

Table 5-3: Scenario analysis results from objective function 1 solutions

Scenario		Optimal costs minimisation (Unit : Baht)	Percentage changes from baseline scenario
Baseline		16,045,402,681	
1	Optimal costs network: four gateway nodes (Songkhla, Suratthani, Nakhon Si Thammarat, Trang)	15,888,584,383	-0.98%
2	GHG emissions optimal network: five gateway nodes (Songkhla, Suratthani, Nakhon Si Thammarat, Trang, Chumporn)	15,888,584,383	-0.98%
3	Four gateway nodes with new route R15	15,875,635,014	-1.06%
4	Five gateway nodes with new route R15	15,875,635,014	-1.06%

Table 5-4: Scenario analysis results from objective function 2 solution

Scenario		Optimal GHG emissions minimisation (Unit : Ton)	The percentage changes from baseline scenarios
Baseline		191,479	
1	Optimal costs network: four gateway nodes (Songkhla, Suratthani, Nakhon Si Thammarat, Trang)	190,787	-0.36%
2	GHG emissions optimal network : five gateway nodes (Songkhla, Suratthani, Nakhon Si Thammarat, Trang, Chumporn)	188,375	-1.62%
3	Four gateway nodes with new route R15	190,787	-0.36%
4	Five gateway nodes with new route R15	188,375	-1.62%

The results of the scenario analysis from the objective function 1 solution show that the percentages of cost savings from scenarios 1 to 4 (see Table 5-3) are 0.98%, 0.98%, 1.06%, and 1.06% respectively. It can be seen that scenarios 3 and 4 show the highest percentage of costs saving as compared to the baseline results. However, since scenarios 3 and 4 results in the same cost reduction, the fifth gateway node in scenario 4 is considered redundant in this analysis. Consequently, the optimum network designed at four gateway nodes, with the development of the new route, R15, is only the best solution from a cost perspective only. It is again worth mentioning that the potential savings from scenario 3 would be 1.06% above the baseline. This amounts to 2,760 million Baht or USD 92 million. In addition, compared to the current industrial situation, the savings would be 2.73% which equates to 7,051 million Baht or USD 235 million. The results of the scenario analysis also show that the optimum number of five gateway nodes, or five gateway nodes with R15, produce the lowest GHG emissions. This is a 1.62% reduction in GHG emissions when measured against the baseline, as shown in Table 5-4. Nevertheless, the new route R15 in scenario 4 is not necessary as the network to have five gateway nodes (scenario 2) and five gateway node with new route R15 (scenario 4) give the same GHG emissions reduction. Therefore, the analysis shows that the restructuring of the distribution to five gateway nodes (without R15) in scenario 2, is the most effective scenario of the four in terms of contributing to the lowering of GHG emissions.

5.5 SUMMARY

In this chapter, the relationship between costs and GHG emissions in outbound distribution networks was examined. In addition, the impact of the restructure of transportation and distribution on costs and GHG emissions was also explored.

The transportation infrastructure analysis, together with the modified model and the distribution network restructuring analysis provides the following new information:

- In terms of economic advantages, distribution network restructuring provides greater benefit to the industry than does capacity development for the transportation service. The restructuring of the network to include four or five gateway nodes has the potential to save the rubber industry 2.13% (6,841 million Baht or USD 228 million) in costs. Further development of the new transportation route, R15, has the potential to achieve higher cost savings of up to 2.21% (7,052 million Baht or USD 235 million) per year for the industry as it currently stands.
- From an environmental standpoint, the restructuring of rail freight service capacity shows an extremely positive result. The potential of a reduction of 5.5% in GHG emissions, by increasing rail freight capacity by 100%, is the optimum scenario. Unfortunately, 100% rail freight capacity improvement is not a realistic figure in the current situation. Considering a more achievable level of 25%, the reduction in GHG emissions was indicated as 3.4%. However, when taking investment costs and time to improve the rail freight service into account, this strategy may not feasible. Furthermore, although this scenario has a positive environmental impact, from an economic perspective there is no positive return. Therefore, this scenario may be not worthy of consideration by the industry. In this regard, the distribution of the restructured network to cover five gateway nodes may be a preferable option. The restructuring of the distribution network with five gateway nodes brings the environmental benefit of a 1.62% reduction in GHG emissions whilst producing an economic benefit of 0.98% in cost savings as compared with the baseline model, or 2.65% when compared to the current economic situation in the industry.

The analysis in this chapter does not encompass all the important aspects of the benefits of each scenario, particularly regarding the return on investments. However, it is believed that these findings can guide decision-makers in making improvements with regard to costs and environmental performance. This chapter not only provides insights for policy makers in terms of policy-support but also contributes to the literature on the Thai Rubber supply chain along with infrastructure modelling for the redesign of the supply chain network. As detailed earlier, the findings argue the claims made by Wasusri and Chaichompoo (2008) and Kritchanchai (2009) regarding the benefits of rail freight and short-sea shipping development to the economy. The new analysis shows that the development of rail freight services and short-sea shipping capacity has no valuable impact upon costs unless the distribution network is restructured. Furthermore, the results of restructuring the distribution network support Harris et al. (2011) who state that the optimum design based on costs does not necessarily equate to the optimum solutions for reducing GHG emissions.

The single objective optimisation developed in Chapter 4, the modified model formulated in this chapter, and the scenario analysis to assess the impact of restructuring has provided new insights for Thai Rubber industry policy makers. However, the trade-offs between costs and GHG emissions have not been taken into account. In Chapter 4 (industrial practice optimal solution), it seems that a reduction in GHG emissions occurs as a consequence of cost reductions in outbound distribution. However, the modified model implemented in this chapter shows that this is not always the case when transportation and distribution networks are restructured. For this reason, it is necessary to consider both economic and environmental criteria as the bi-objective functions to capture the trade-offs between these two objectives in the supply chain network. Without considering the bi-objective optimisation model, Thai Rubber industry policy makers are likely to make decisions that may lead to fulfilling one objective while jeopardising the other.

The next chapter addresses the limitations of single-objective optimisation by demonstrating the multi-objective optimisation model, which redesigns the management of the green supply chain for the Thai Rubber supply industry.

CHAPTER 6

MULTI-OBJECTIVE OPTIMISATION: TRADE-OFFS BETWEEN COSTS AND GREENHOUSE GAS EMISSIONS

6.1 INTRODUCTION

In Chapter 4, costs and GHG emission measures from inbound logistics and manufacturing data showed conflicting results, while those for outbound logistics were compatible (section 4.7). However, the modified model implemented, and its scenarios analysis in Chapter 5, shows that for outbound distribution, these two objectives are conflicting when transportation and distribution networks are restructured (section 5.4). In its current state, the relationship between costs and GHG emissions in the Thai Rubber supply chain appears to be conflicting in nature.

As mentioned in Chapter 5, when Thai Rubber industry policies are created using single-objective optimisation in decision-making, this can lead to the achievement of one objective, while jeopardising the other. This is the case with costs and GHG emissions in the current study. Hence it is necessary to incorporate these two objective functions into a bi-objective optimisation model in order to capture the trade-offs between costs and GHG emissions in the supply chain network. These considerations have led to the multi-objective optimisation problem, in which the solutions comprise a set of Pareto optimal points that make simultaneous trade-offs when considering the objectives. Wang, Lai and Shi (2011) mention that multi-objective optimisation provides more practical results for actual applications than single objectives. In addition, Guillen-Gosalbez et al. (2010) highlight multi-objective optimisation as an adequate method for the incorporation of environmental concerns when optimising the supply chain.

There are different techniques for solving problems involving multiple objectives. Guillen-Gosalbez et al. (2010) have classified certain techniques for use in solving multi-objective optimisation problems into three approaches. The first approach is based on the transformation of the problem into a single objective using single-objective optimisation to solve the problem (Ehrgott 2000). The second approach is the non-Pareto method which uses search operators based on the objective to be optimised. The general concept of this method can be found in Blanke et al. (2008). The third approach is the Pareto method. This technique generates a set of solutions to the trade-offs for different objectives (Deb 2005). As the objective of this chapter is to find the Pareto optimal solution, this approach will be employed to investigate the trade-offs between cost and GHG emissions minimisation in the Thai Rubber supply chain. In this way, it will be possible to provide the decision-maker with sufficient alternative options to make decisions when making trade-offs between the relative conflicting objectives.

For the calculation of the Pareto set, two basic methods exist in the literature. These are the Weighting Method and the ε -Constraint Method (Miettinen 2008). In recent years, some of the literature has pointed out the drawbacks of using the weighting method and the advantages of using the ε -constraint method (Caramia and Dell'Olmo 2008; Miettinen 2008; Gebreslassie et al. 2009). In addition, the ε -constraint method has been widely used to solve many multi-objective problems in the GSCM, as attested by the work of Hugo and Pistikopoulos (2005), Guillen-Gosalbez et al. (2010), and Kim, Janic and Wee van (2010). The ε -constraint method was therefore adopted to compute the Pareto optimal solution for the more effective management of the Thai Rubber supply chain.

This chapter aims to addresses the limitations of single-objective optimisation by adopting the multi-objective optimisation model (with particular focus on the bi-objective element) for the Thai Rubber supply chain. The objective is to generate a full set of trade-off solutions for both costs and GHG emissions. From the set of alternative solutions, the decision-maker can investigate and select the supply chain network design that most satisfies their preferences.

In this chapter, the general formulation of multi-objective optimisation is reviewed. It is followed by mathematical formulations and solution procedures to solve the multi-objective optimisation problem. The Pareto optimal solutions to costs and GHG emissions are then presented and discussed. The scenario analysis in this chapter was conducted to explore the trade-off solutions to four transportation and four distribution-restructure scenarios from Chapter 5. While the scenarios analysis illustrated the trade-off curves in each scenario, particular attention was paid to the interpretation of the curve pattern. At this stage, newly obtained insights to support future policy implementation were analysed. The chapter concludes by presenting valuable insights obtained from the Pareto optimal solution and its scenarios analysis, with regard to the design of the Thai Rubber GSCM model.

6.2 MULTI-OBJECTIVE OPTIMISATION

In multi-objective optimisation problems, no unique solution exists. However, there are a number of solutions that are equal to one another in terms of effectiveness. These solutions are known as Pareto optimal solutions (Miettinen 2008).

The general formulation for multi-objective optimisation can be expressed as follows (Blanke et al. 2008):

$$Min \ \{f_1(x), f_2(x), \dots, f_k(x)\}$$

Subject to $x \in S$

Where

- $k(\geq 2)$ is the conflicting objective functions $f_i : \boldsymbol{R}^n \rightarrow \boldsymbol{R}$, where $\boldsymbol{R}$ denotes the set of real numbers
- The decision variable vectors $x = (x_1, x_2, \dots, x_n)^T$ belong to the non- empty feasible region $S \in \boldsymbol{R}^n$

- Objective vectors are images of decision vectors and consist of objective function value $z = f(x) = (f_1(x), f_2(x), \dots, f_k(x))^T$.

A decision vector $X' \in S$ is known as Pareto optimal if another $X \in S$ does not exist such that $f_i(x) \leq f_i(x')$ for all $i = 1,..,k$ and $f_i(x) < f_i(x')$ for at least one index. In multi-objective optimisation, objective vectors are regarded as optimal if none of their components can be improved without deterioration to at least one of the other components (Blanke et al. 2008). An overview of multi-objective optimisation can be found in Blake et al. (2008). For additional information on multi-objective optimisation applications, refer to Deb (2005).

6.3 MATHEMATICAL FORMULATION

In this chapter, sets, parameters, decision variables, objective functions and constraints are similar to those developed in Chapter 4. These include objective function 1 for cost minimisation, objective function 2 for GHG emission minimisation and constraints 3 to 16 for model constraints (see section 4.3). The model data, parameters and variables are summarised in Appendix Table A-1 to A-25.

In Chapter 4, the Thai Rubber supply chain was presented in two single objective functions, while in this chapter the Thai Rubber supply chain is presented in terms of bi-objective optimisation. The solution to this model is known as the Pareto optimal solution. Each solution within the set represents an alternative to the quantity of rubber product flowing between the supply chain entities (farmer, trader group, and factory) and the transportation mode and route, in order to minimise total costs while at the same time minimising total GHG emissions.

In the next section, the procedure for calculating the Pareto set for the above multi-objective model will be explored.

6.4 SOLUTION PROCEDURES AND MODEL IMPLEMENTATION

In this thesis, the ε -constraint method was adopted to calculate the Pareto set of solutions to problems in the Thai Rubber supply chain. In the ε -constraint method, one of the objective functions in the original problem was selected for optimisation whilst the other objective was converted into constraints (Caramia and Dell'Olmo 2008). The reformulated model is shown below:

$$Min\, Z_1 =$$

$$\sum_i \sum_s \sum_p \sum_t \sum_g X_{isptg}(CR_{sp} + CT_{stg} + CG_{gp}) +$$
$$\sum_i \sum_g \sum_f \sum_e \sum_a Y_{igfea}\left(CT_{igf} + CF_{fe} + CT_{fa}\right) +$$
$$\sum_e \sum_a \sum_b \sum_d Z_{eabd}\,(CT_{ab} + CM_b + CT_{bd}) \qquad (1)$$

Subject to:

Constraints (3)-(16);

$Z_2 \leq \varepsilon$

In this model, if the ε parameter is set at ∞ (infinity, or very large number); the resulting model then solves the single-objective problem of total cost minimisation. In other words, this formulation is a generalisation of the cost minimisation model developed in Chapter 4. On the other hand, if ε parameter is set to too small a value, the resulting problem is infeasible. In order to avoid these two extreme situations it is firstly necessary to determine reasonable bounds for the ε parameter.

The procedure to calculate the upper and lower boundaries for parameter, ε with the constraints and estimation of the Pareto optimal solution is as follows:

Step 1: Calculate the lower and upper boundaries for the ε parameter (denote them as $\varepsilon_L, \varepsilon_U$ respectively). Based on these boundaries, determine a step (h) to be used to define a partition of the interval ($\varepsilon_k = \varepsilon_L + h \cdot k \ \forall \ k \in K$) with $K \subseteq N$ a finite subset of the natural numbers.

Step 2: for $k \in K$

Step 2.1: Initialise all parameters, objective functions, constraints (3)-(16), and (ε).

Step 2.2: Run linear programming single-objective optimisation function1 (Z_1) with ε_k to get the optimal solution for Z_1 (denoted by $v_k^*(Z_1)$)

Step 2.3: Save the set of ordered values: tuple ($\varepsilon_k, v_k^*(Z_1)$)

Step 3: The collection of points $\{(\varepsilon_k, v_k^*(Z_1))\}_{k \in K}$ is a discrete approximation of the Pareto efficiency frontier.

The intervals between the lower and upper boundaries of ε parameter were partitioned into 50 subintervals of equal length. Calculations within the model were then performed to find every possible value for ε (see table A-38 to A-46 in Appendix for all ε parameter used in this chapter).

The optimisation software ILOG CPLEX version 12.3 was used to formulate and solve the model. All computational work was performed on a personal computer (32-bit operating system, 2.33 GHz CPU, and 4.00 GB). The respective scope was specified by 10,927 variables subjected to 309 constraints. The Pareto optimal solution to solving this bi-objective problem is presented in the following section.

6.5 PARETO OPTIMAL SOLUTION TO MINIMISING COSTS AND GHG EMISSIONS

The Pareto set of solutions for minimising costs and GHG emissions is illustrated in Figure 6-1 (see table A-38 in Appendix for the corresponding table of Pareto set of solutions). All the optimal solutions lie on the Pareto curve. Thus, the solutions above the curve are sub-optimal solutions while any solutions below the curve are infeasible. Each point in the Pareto set entails a specific quantity of rubber product flow between the supply chain entities (farmer, trader group and factory) and the transportation modes and routes. The marginal point at the upper left (point A) is the extreme solution for GHG emissions minimisation whereas the marginal point at the lower right (point C) is the extreme solution to cost minimisation.

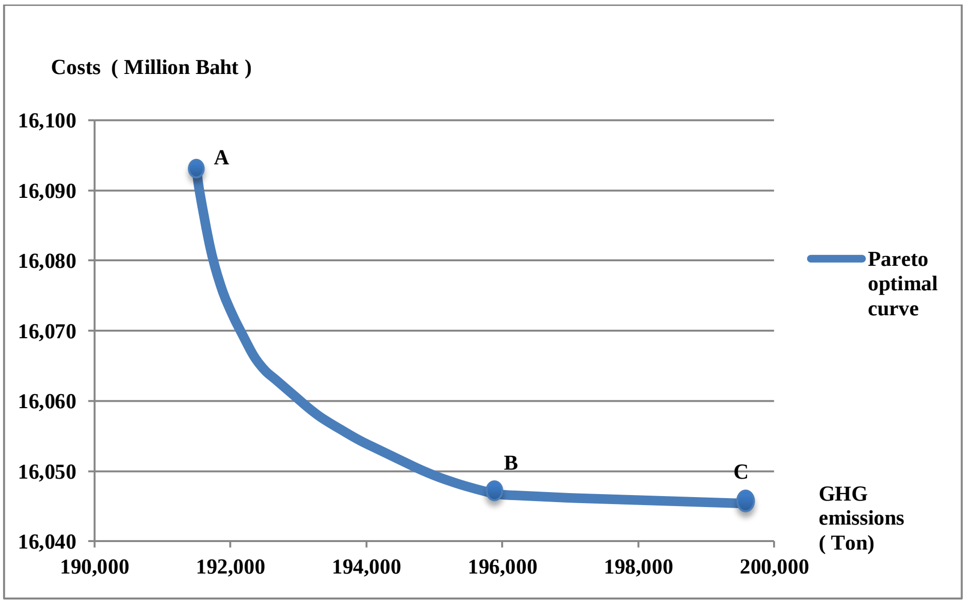

Figure 6-1: Pareto curve of costs and GHG emissions

The Pareto optimal in figure 6-1 clearly demonstrates the trade-offs between costs and GHG emissions. It shows that cost reduction is only possible by making a compromise with regard to higher GHG emissions. The X and Y-axes in the Pareto optimal graph are GHG emissions in tons and costs in millions of Baht. The vertical length and horizontal width of the graph represent the decrements in costs and increments in GHG emissions. These can be used to indicate changes in costs relative to GHG emissions. Upon analysis of the results, the Pareto curve shows two distinct patterns. The first pattern from point A to point B shows the curve starting to move from left to right, with a drastic reduction in costs relative to the minimal increments in GHG emissions, before the curve continues with a lesser decrement in costs but a greater increment in GHG emissions. The Pareto curve then exhibits the second pattern from point B to point C. The Pareto curve is almost a flat line. It shows that a very minimal reduction or no reduction in costs produces a significant increment in GHG emissions before the curve moves towards the extreme solution for cost minimisation at point C.

From these alternative solutions, policy makers in the Thai Rubber industry can choose the best-fit solution, according to preference and applicable policy. Although environmental responsibility is currently voluntary in the Thai Rubber industry, the policy maker can begin to consider making environmental improvements for a marginal increase in total costs. Although each point in the Pareto optimal curve is equally effective at representing different solutions to or compromises between these two objectives, it is possible to find a ‘good choice’ solution in the above curves. The solution in point B may be a promising answer in that significant cost savings may be made without compromising too far with regard to total GHG emissions. The solution in point B shows that to reduce 1 ton of GHG emissions, the compromise must be an increase of 0.01 million Baht in costs. In future, this measurement could be used to support environmental cost policies. In addition, the Thai Rubber policy maker can use this Pareto curve as a tool to estimate the potential gain in environmental improvements compared with the costs to obtain this gain.

6.6 SCENARIO ANALYSIS

As mentioned previously in Chapter 5, the restructure in transportation and distribution clearly showed a conflict between optimal costs and reduced GHG emissions. This section aims to examine the trade-offs between these two objectives. Eight transportation and distribution restructure scenarios from Chapter 5 were selected to examine the trade-off solutions in each scenario.

For transportation restructure, Scenarios 1 to 4 from Chapter 5 were chosen. These scenarios are related to the capacity of rail freight when it is increased by 25%, 50%, 75% and 100% from the current service capacity. Compared to other scenarios for transportation restructuring, these four scenarios show explicit conflict between optimal costs and GHG emissions reduction. Therefore, trade-off solutions will be useful for policy makers in the Thai Rubber industry. In terms of distribution restructure, the optimal cost solution at four gateway nodes, five gateway nodes and four and five gateway nodes, with the new route R15 trade-off curves, will be explored in this section.

The descriptions of transportation and distribution restructure scenarios are presented in Table 6-1 and 6-2 as follows:

Table 6-1: Transportation restructure scenarios

Scenario	Description
1	Increase rail freight service capacity by 25% (Route R5, R6, R7, R10, R11, R12, R13)
2	Increase rail freight service capacity by 50% (Route R5, R6, R7, R10, R11, R12, R13)
3	Increase rail freight service capacity by 75% (Route R5, R6, R7, R10, R11, R12, R13)
4	Increase rail freight service capacity by 100% (Route R5, R6, R7, R10, R11, R12, R13)

Table 6-2: Distribution restructure scenarios

Scenario	Description
1	Four gateway nodes
2	Five gateway nodes
3	Four gateway nodes with new route R15
4	Five gateway nodes with new route R15

The Pareto curve for transportation and distribution scenarios compared with the baseline model is presented in Figures 6-2, 6-3, 6-4 and 6-5. These figures have the same scale in each panel. Moreover, the baseline Pareto curve from Figure 6-1 was re-scaled in order to make comparisons between each scenario.

6.6.1 Transportation scenarios - Pareto optimal solutions

The Pareto curves in Figure 6-2 show that when increasing the capacity of rail freight, the curve moves from right to left in a straight line to the upper left side of the panel. In each scenario, rail freight capacity is increased by 25% to baseline (see table A-39 to A-42 in Appendix for the corresponding table of Pareto set of solutions in each scenario).

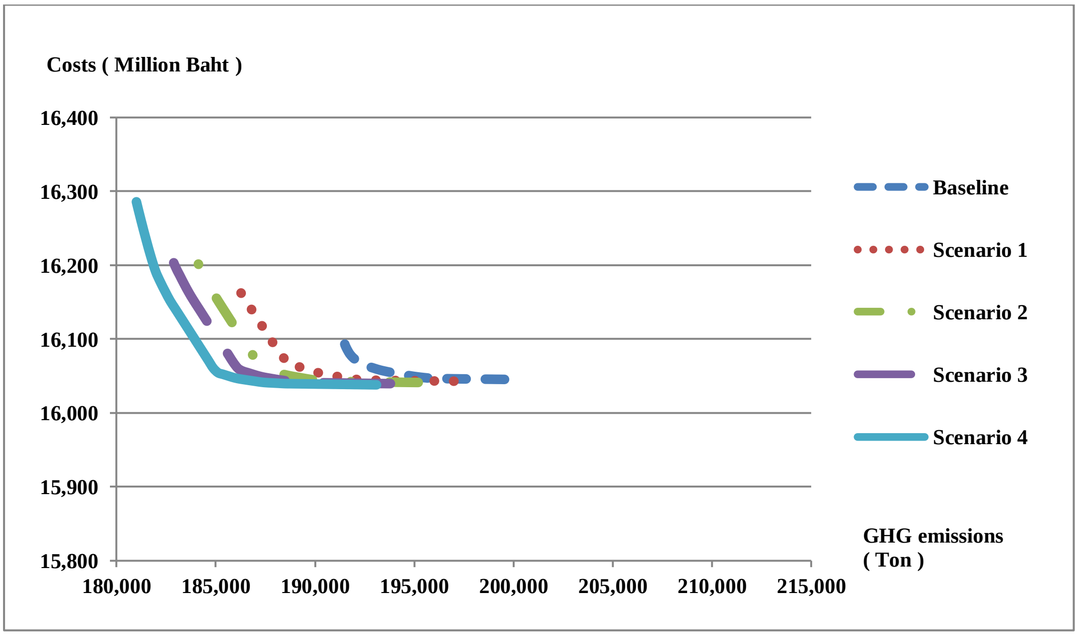

Figure 6-2: Pareto curves of four transportation restructure scenarios

These curve patterns strongly suggest that at the same cost level, an increase in rail freight service capacity leads to lower GHG emissions at the same proportional rate as the increase in rail freight capacity. With regard to the same total GHG emissions, there are two observations related to cost reduction. The first observation concerns GHG emission levels for loads lower than approximately 190,000 tons. It shows that at the same level of GHG emissions, costs gradually and continuously increase relative to the lower rail freight capacity ratio. The second observation concerns GHG emission levels for loads greater than 190,000 tons. The Pareto curves in all scenarios become flat and overlapping, meaning that GHG emission levels become increasingly independent of costs. There are no or very minimal reductions in costs, but the GHG emissions continue to increase until entering the realm of extreme solutions for the minimising of costs. This is a significant finding for policy makers in that any solutions in this curve range may not be effective choices as trade-off solutions. In other words, when costs reduce to a certain level, it is not worth reducing them further, as a compromise must be made with the greater increases in GHG emissions.

Furthermore, it can be seen that when rail freight capacity is increased from the baseline by 25% (Scenario 1), this results in a greater shift of the curve from right to left. When this occurs, the other scenario curves shift consecutively with equally smaller proportional ratios. This suggests that an increase in the first 25% of rail freight capacity has a greater impact on the reduction of GHG emissions. Consequently, Scenario 1 may be a more effective solution compared to the other scenarios, particularly when taking into account actual rail freight capacity with regard to feasibility. As indicated in the previous chapter, a 25% increase in rail freight capacity is the most realistic scenario based on current infrastructure facilities (MOT 2007). However, it is worth observing with regard to Scenarios 2 to 4, the greater the capacity of the rail freight operation, the lower the GHG emissions.

Improvements in rail freight capacity will unavoidably incur investment costs. Therefore, policy makers must decide whether it is worthwhile to do so, using the Pareto curves as a guide. For example, with GHG emissions reduction as a goal, the policy maker will be able to estimate the cost difference between the baseline and each scenario. If the cost difference is large enough to cover the investment in rail freight capacity improvement, then this goal is worthwhile. Otherwise, the search for alternative trade-off solutions must continue. More specifically, if Thai Rubber industry policy makers set GHG emission levels at 191,500 per ton as a goal, the cost difference between the baseline and Scenario 1 is 46 million Baht (16,093 and 16,047 million Baht for the baseline and Scenario 1 respectively). Thus, if the investment costs of upgrading rail track facilities are lower than 46 million Baht, it is worthwhile pursuing the strategy in Scenario 1.

In summary, the Pareto curves for the restructuring of transportation presented in this section provide clear solutions for policy makers regarding the impact on costs and GHG emissions. As discussed in chapter 5, an increase in rail freight capacity resulted in minimal impact on cost reduction but it had a significant impact on the reduction of GHG emissions. These conflicting solutions make decision-making difficult for policy makers. The Pareto optimal results and the trade-off curves presented in this section are intended to overcome that limitation.

6.6.2 Distribution scenarios - Pareto optimal solutions

Figure 6-3, 6-4, 6-5 and 6-6 below illustrate the Pareto curve for the baseline and four different scenarios related to distribution restructure (see table A-43 to A-46 in Appendix for the corresponding table of Pareto set of solutions in each scenario). In Figure 6-3, the Pareto curves only show two visible curves for the baseline and Scenario 4, as the curve for Scenarios 1, 2 and 3 lie under the curve in Scenario 4. Therefore, Figure 6-4, 6-5 and 6-6 are presented to show in order to view the individual Pareto curve in Scenarios 1, 2 and 3.

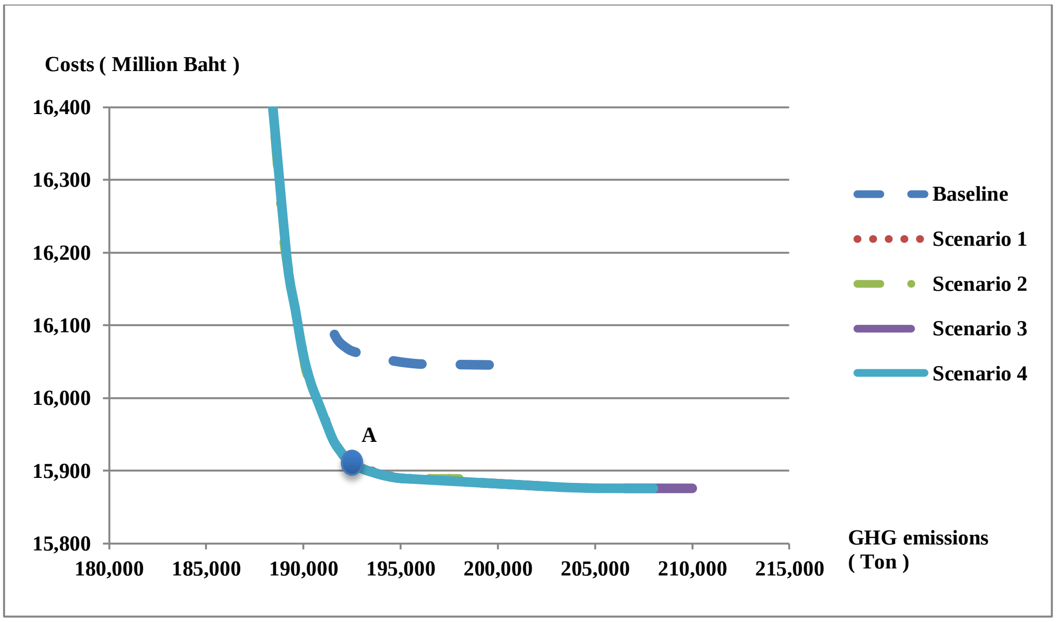

Figure 6-3: Pareto curves of four distribution restructure scenarios

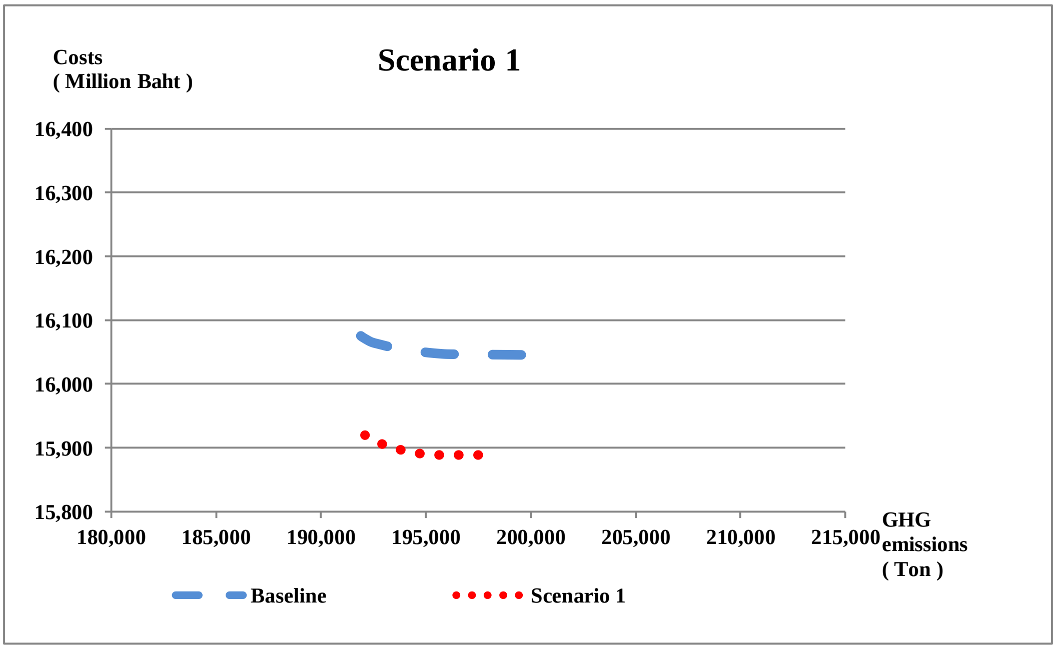

Figure 6-4: Pareto curves of distribution restructure Scenario 1

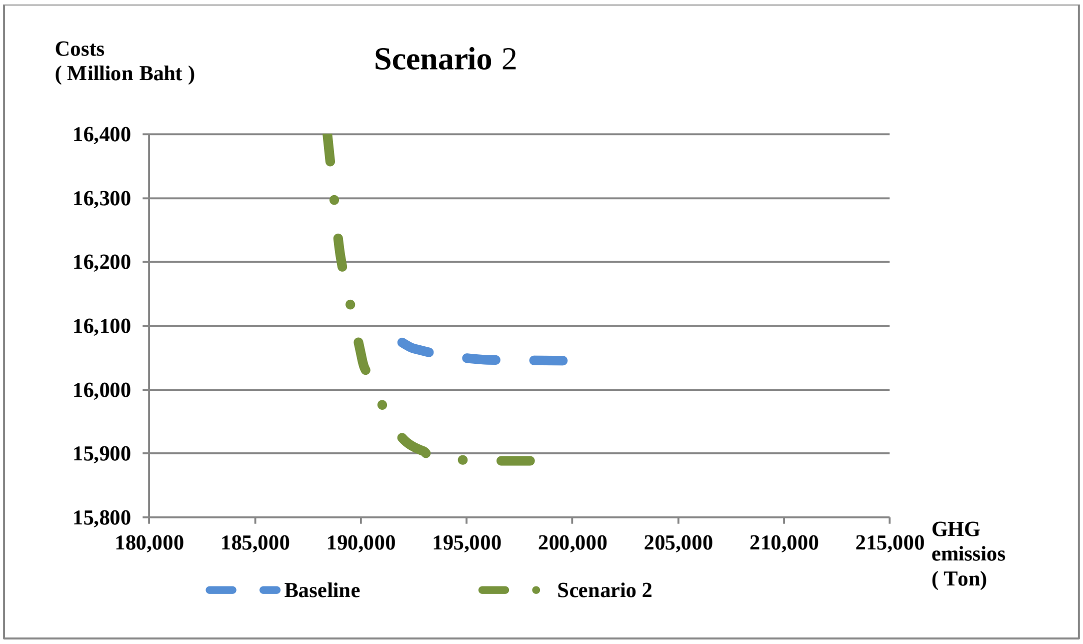

Figure 6-5: Pareto curves of distribution restructure Scenario 2

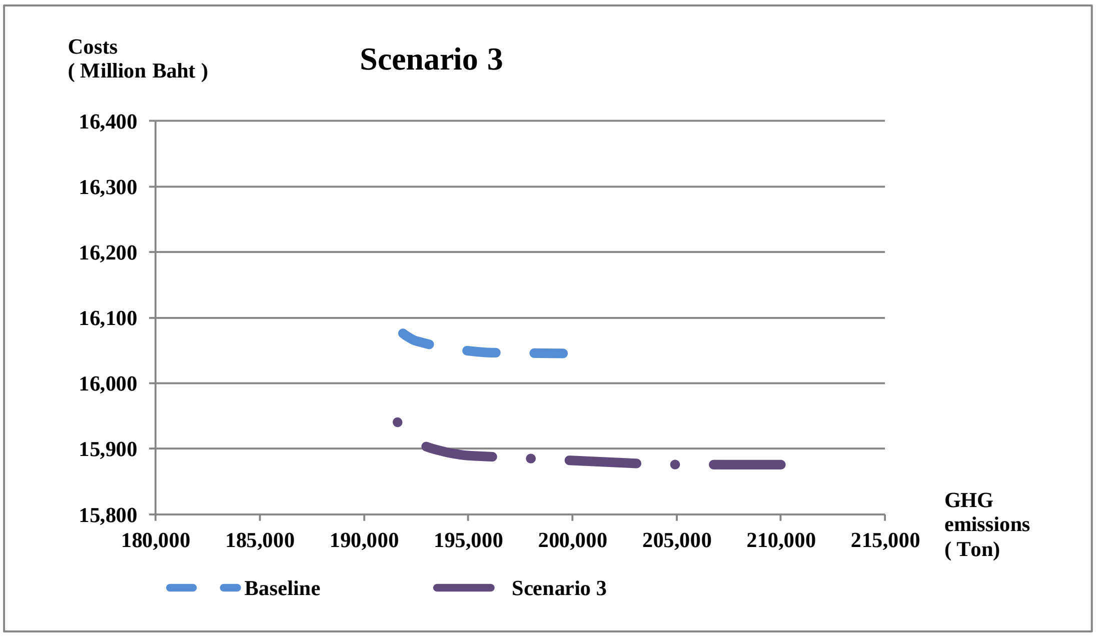

Figure 6-6: Pareto curves of distribution restructure Scenario 3

The Pareto curves for distribution restructure show that at four gateway nodes, the curve moved sharply to the lower bottom panel (see Figure 6-4). Likewise with the five gateway nodes the curve moved to the lower bottom of the panel. However, for the five gateway nodes, the curve shape changed with a lengthening of the straight line to the upper left side (see Figure 6-5). The curve pattern suggests that at the same GHG emissions level, the more gateway nodes, the lower the cost. In addition to the curve shape, it can be noticed that the Scenario 1 curve is a portion of the Scenario 2 curve.

For Scenarios 3 and 4, when the new transportation route R15 is implemented in conjunction with four and five gateway nodes, the graph shows the same pattern as Scenario 1 and 2. It can be seen that for Scenarios 1 and 3, curve patterns 2 and 4 are almost the same. The differences between these curves are that the scenario curves for route R15 lengthen in a straight horizontal line to the bottom right panel before entering the area of the extreme cost minimisation solution.

Another important insight obtained from Figure 6-3, 6-4, 6-5 and 6-6 is that the curves of these four scenarios lie under and overlap each other. The curves clearly show that Scenario 1 is a part duplication of Scenario 3 while Scenario 2 is a part duplication of Scenario 4. Overall, Scenarios 1, 2 and 3 are part duplications of Scenario 4. In addition, these four curves have the same turning point (point A) on a flat horizontal line. This information suggests that Scenario 4 may be the most promising, with point A as an effective solution to achieving significant cost savings without compromising too far on GHG emissions.

6.6.3 The comparison of transportation and distribution Pareto optimal solutions

This section aims to present the Pareto curves for the selected transportation and distribution restructure scenarios. As discussed in the above section, Scenario 1 for transportation is the most realistic scenario for achieving significant GHG emission reductions without compromising too far with regard to increased costs. In addition, Scenario

4 is considered to be one of the most promising scenarios for achieving a notable cost reduction without compromising greatly on GHG emissions. It is therefore worthwhile to further examine the relationship between these two scenarios' Pareto curves.

Figure 6-7 depicts the Pareto curves for transportation in Scenario 1 (see Scenario 1: T curve), and distribution Scenario 4 (see Scenario 4: D curve) and the baseline model.

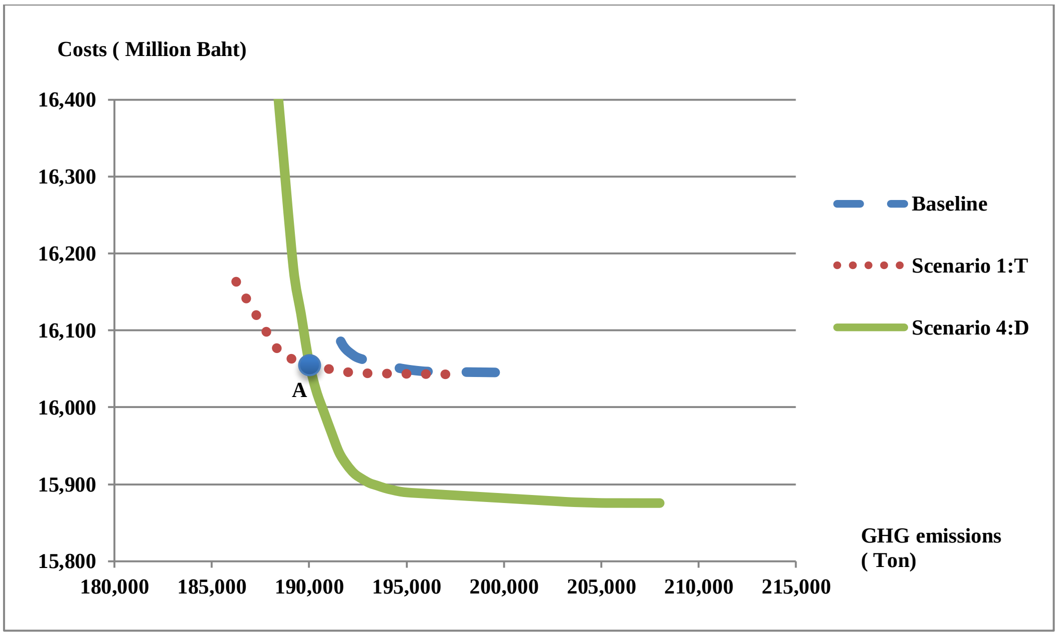

Figure 6-7: Pareto curves of baseline, Scenario 1 for transportation and Scenario 4 for distribution.

It is clearly shown from figure 6-5 that at the same costs level, Scenario 1: T indicates lower GHG emissions while the same GHG emissions level for Scenario 4: D exhibits lower costs. The interesting point about this figure is the Pareto curve of these two scenarios which intersects at point A. This is the point where transportation and distribution restructuring scenarios have the same solution. The optimal solution at this point for simultaneous cost and GHG emission reductions would be where GHG measures are taken at a load level of 189,968 tons and the total costs would be 16,062 million baht. Therefore, if the policy maker were to select this solution, it could be implemented by adopting either transportation restructure Scenario 1 or distribution restructure Scenario 4.

When analysing the curve in more detail, it is possible to pinpoint A as necessary to scenario selection criteria. It can be seen that where GHG emission levels are higher than the 189,968 measure, Scenario 4: D provides the better compromise. Scenario 4: D indicates a higher cost reduction with a marginal GHG emissions increase than does Scenario 1:T. On the other hand, for a GHG emissions level lower than the 189,968 measure, only Scenario 1: T will produce a feasible solution. For this reason, policy makers must focus clearly on GHG emission targets in order to achieve their goals. It is important to note that different GHG emissions target levels will lead to different strategies for achieving the target by using the best compromise.

In summary, the analysis of the Pareto curves in this section highlights that it is possible to provide a solution with two alternative scenarios. These scenarios relate to either increasing rail freight services or setting up more distribution centres. It is important to point out that the more stringent the GHG emissions target, the greater the rail operation needed. On the other hand, if the GHG emissions target is a consideration, but not the ultimate priority, the strategy for achieving environmental gains without increasing costs for trade–offs would be to set up more distribution centres.

6.7 SUMMARY

In this chapter, a multi-objective linear programming model was developed which sought to simultaneously optimise total costs and total GHG emissions for the Thai Rubber supply chain. The model was solved by the ε -constraint method which computed the Pareto optimal solution. Each point in the Pareto set entailed a different design of quantity of rubber product flow between the supply chain entities and transportation modes and routes. The main advantage in this approach is that it produces a set of alternative options for a supply chain design rather than a single solution. From these alternatives, the decision maker can choose the best-fit solution according to preferences and applicable policies.

The results obtained show the trade-offs between costs and GHG emissions. It appears that improvements in cost reductions are only possible by compromising on and allowing for higher GHG emissions. From the Pareto set of solutions, each point is equally effective in representing a compromise solution. However, it is possible to identify an effective solution for achieving significant cost reductions without compromising too far on GHG emissions. As indicated in section 6.4, the solution at the point before the curve turns into a flat line is considered a positive solution.

From the scenario analyses, it can be concluded that transportation restructure is more beneficial to the environmental than a distribution restructure. The greater the increase in rail freight, the less GHG emissions in the supply chain. In this thesis, an increase of 25% in rail freight capacity is seen as the most feasible scenario leading to lower GHG emissions without great cost compromises. From an economic perspective, restructuring distribution to five gateway nodes, along with the development of route R15, will result in notable cost reductions.

Finally, although environmental safeguarding measures are currently voluntary in the Thai Rubber industry, the policy maker can begin to take environmental issues into account when considering changes to the supply chain design. The Pareto solution obtained from this chapter has suggested an alternative supply chain network which will lead to both economic gain and environmental improvement. In particular, it was shown how policy makers may use this tool to compare the potential gain in environmental improvements against the costs of obtaining this gain. This measure can be used as an indicator to support any policy regarding environmental issues, such as environmental cost policies. Overall, the model developed in this chapter, together with its Pareto optimal solutions analysis, shows that it can be used as an effective tool to design a new and workable GSCM model for the Thai Rubber industry

CHAPTER 7

DISCUSSION:

ANALYSIS OF MODEL RESULTS AND RUBBER ZONING GUIDELINES

7.1 INTRODUCTION

This thesis has been written with a focus on providing a decision-support model for Thai Rubber industry policy makers to better manage the Thai Rubber supply chain. The policy makers in the industry consist of government agencies involved in rubber industry activities such as plantation activities, production and marketing. The reason that this thesis focuses on government agencies is due to their role in, and influence over the industry. They play an important role in managing the rubber industry from the regional to the international level. Moreover, they also have the power to create laws, rules and regulations to control rubber prices, plantation zoning and marketing trading mechanisms. Another important reason is that these agencies are able to facilitate the expansion of, or investment in distribution and transportation facilities such as distribution centres, roads, railways and port terminals. With regard to environmental concerns, it is clear that policy makers could take the initiative in urging the private sector to look into their entire supply chain and create "green" objectives even though this is not yet compulsory.

The following section discusses the results analysis with regard to policy implementation. These results should assist those in the Thai Rubber supply chain to achieve a balance between economic gain and environmental responsibility.

7.2 RUBBER ZONING

As discussed in the previous chapter, the main rubber activities and export gateways are Songkhla, Suratthani and Nakhon Si Thammarat. The number of rubber plantations and manufacturers in these provinces has been steadily increasing. This growth is strengthening industry competitiveness. However, without a controlled plan and policy guidelines for the expansion of rubber facilities and transport infrastructure this disorganised or unstructured growth may actually constrain industry competitiveness.

Various developments in the industry have created more unnecessary layers in the supply chain, resulting in increased costs and pollution. This has also created ineffective utilisation of rubber plantation capacity and transport infrastructure. In some instances, the inadequacy of road, rail or sea transport has increased transportation costs and decreased service levels in the industry. In addition, the concentration of labour in certain provinces has also caused labour problems in the industry.

The single-objective optimisation model results in Chapter 4, along with the scenarios analysis in Chapter 5 can assist in optimising the current industrial supply chain network and linkage between supply chain entities. The model also allocated optimal production capacities for each province. In addition, the multi-objective optimisation model in Chapter 6 provided the set of Pareto solutions that simultaneously optimised costs and GHG emissions in the supply chain. From the set of trade-off solutions, policy makers can select the supply chain network design that most satisfies their preferences and applicable policies. As a result, the possibilities for improving economic performance without worsening the environmental performance of the Thai Rubber supply chain were identified.

In the following section, model results analysis will be discussed and used to propose the establishment of rubber zoning guidelines. Rubber zoning can be used to support any policy related to the rubber industry. This includes: land use control for new plantations, rubber manufacturer zoning, number of traders in each region and transport infrastructure investment. Primary research into the Thai Rubber industry pointed out that the unstructured supply chain puts constraints on the rubber industry's competitiveness (Wasusri and Chaichompoo 2008; Kritchanchai 2009; Kritchanchai, Somboonwiwat and Chanpuypetch 2010). Rubber zoning aims to address this current industry weakness. It is important to note that the rubber zoning proposal discussed in this chapter is given for general guideline purposes, rather than being a presentation of a comprehensive and detailed policy.

The establishment of rubber zoning is proposed through three development levels, according to the readiness of current industry in terms of facilities and with regard to ease of implementation. The three levels are as follows:

- Primary level rubber zoning implementation
- Intermediate level rubber zoning implementation
- Trade-off level rubber zoning implementation

7.2.1 Primary level rubber zoning implementation

Primary level rubber zoning is based on the model results from Chapter 4 which optimised the supply chain in current industrial practice. This zoning level is ready for implementation in that it does not require expansion of current transportation and distribution facilities. It is important to note that this level of rubber zoning is proposed from a single objective perspective (i.e., economic or environmental). Hence in practice, the policy maker has to select which objective they wish to implement.

Primary level rubber zoning implementation is divided into three network flow-zone areas. Figures 7-1 and 7-2 support the establishment of economic competitiveness and environmentally friendly rubber zoning. Even though the rubber zoning and network linkage for these two objectives are the same, the allocations for farmer and factory production capacity are different.

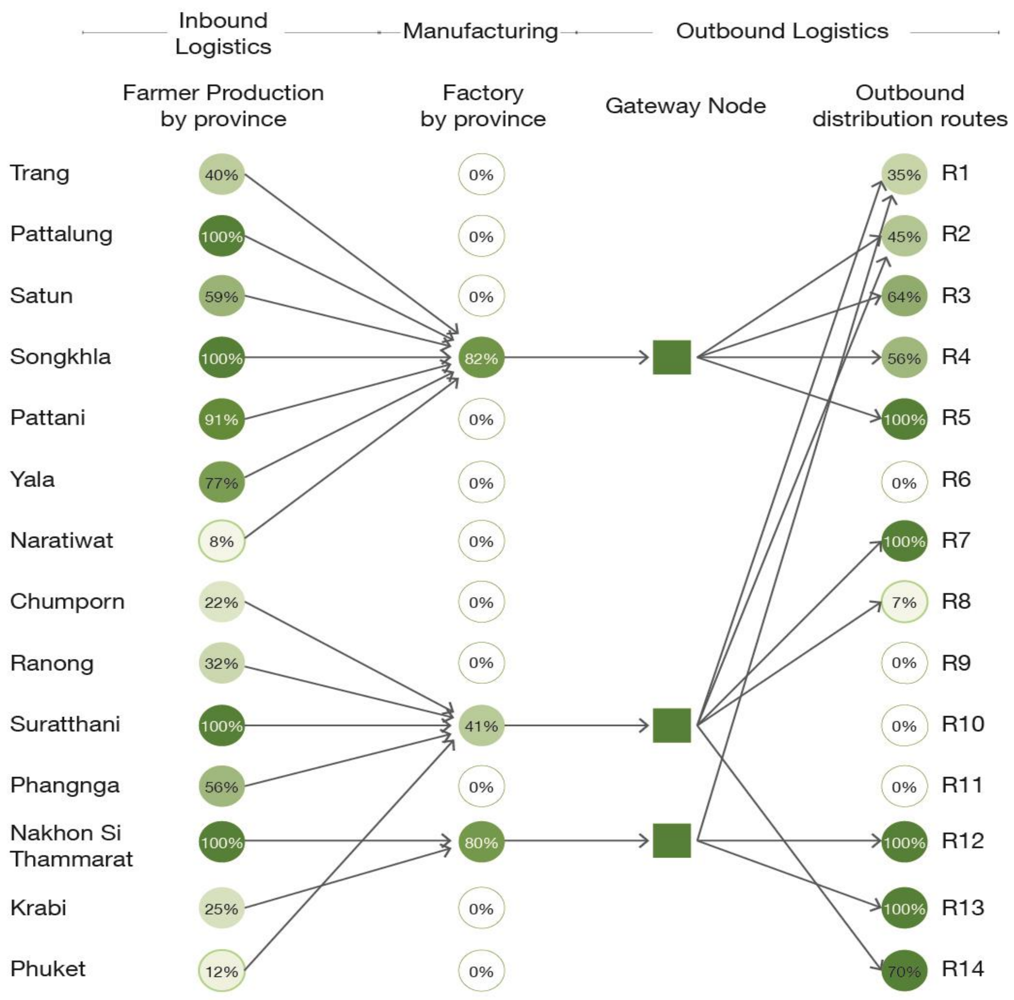

Figure 7-1: The economically competitive rubber zoning network flow – the primary level (repeated in Figure 4-6)

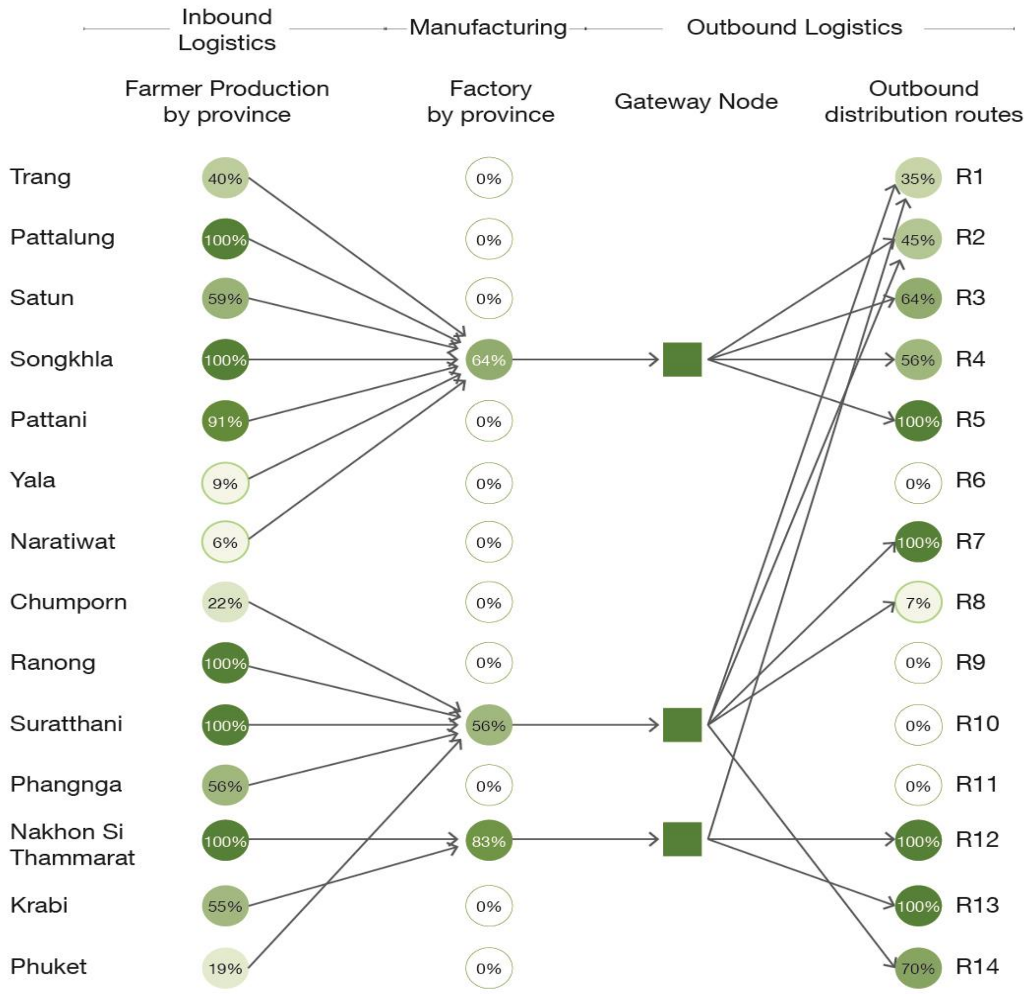

Figure 7-2: The environmentally friendly rubber zoning network flow- the primary level (repeated in Figure 4-7)

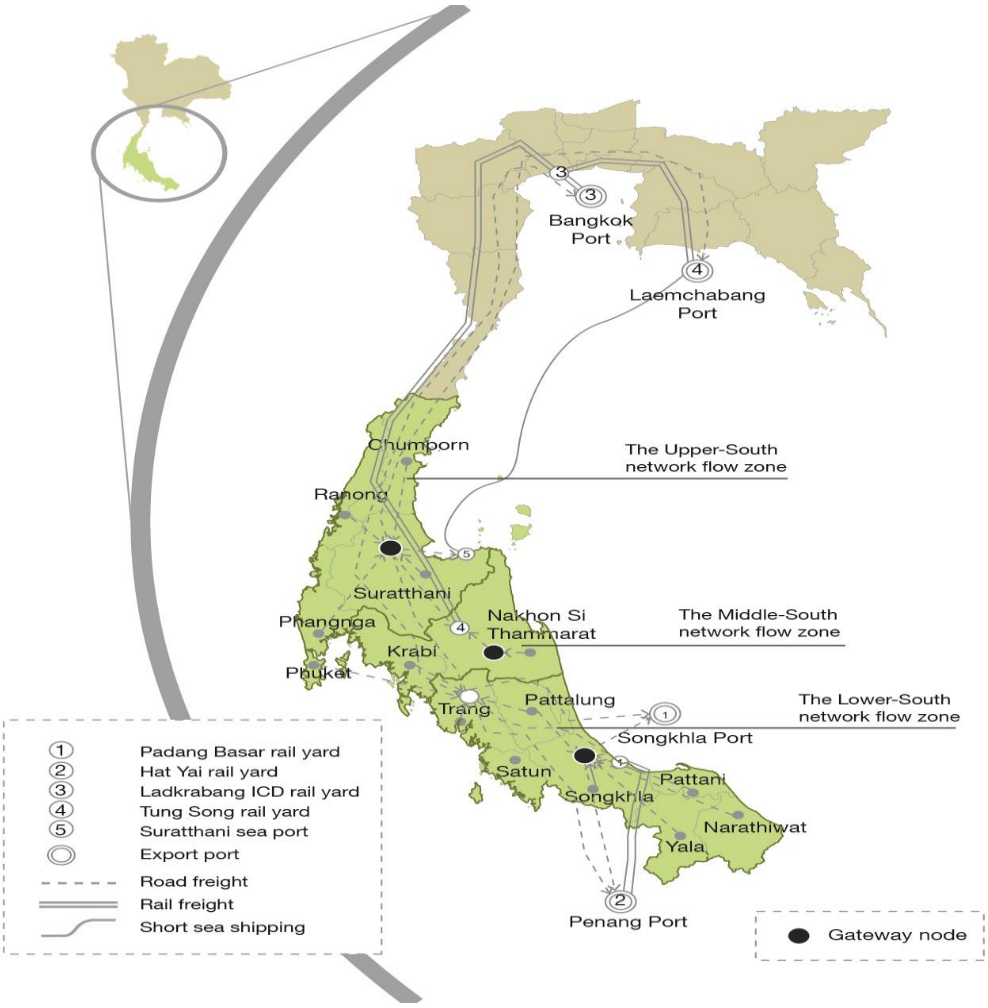

Figure 7-3: The primary level rubber zoning areas

The primary level rubber zoning areas for economic competitiveness and environmental friendliness can be divided into three rubber network zones (See Figure 7-3) as follows:

- *The Lower-South network flow zone:*

  This zone comprises seven provinces (Trang, Pattalung, Satun, Songkhla, Pattani, Yala and Narathiwat). The primary rubber products from this network are sent to the factory in the Songkhla province to produce intermediate rubber products which are then transported through routes R2, R3 and R4.

- *The Middle-South network flow zone:*

  There are two provinces in this network flow zone: Nakhon Si Thammarat and Krabi. The primary rubber products from this network flow are sent to Nakhon Si Thammarat province and subsequently transported through routes R1, R12 and R13.

- *The Upper-South network flow zone:*

  There are five provinces in this network flow zone. The provinces in this network flow zone include Suratthani, Chumporn, Ranong, Phangnga and Phuket. The products from these provinces are sent to the factory at Suratthani and then transported through routes R1, R2, R7, R8 and R14.

The benefit of primary level rubber zoning is that the total cost of rubber production would be improved by 1.56% relative to current industrial practice (see Chapter 4, section 4.7.1). This is equivalent to 4,148 million Baht per year or approximately USD138 million per year. With regard to GHG emissions minimisation, total GHG emissions per ton of rubber product would be 1.08 tons (see Chapter 4, section 4.7.2).

7.2.2 The intermediate level of rubber zoning implementation

This level of rubber zoning implementation focuses on the improvement of the supply chain network through the restructure of the distribution network. In Chapter 5, the newly restructured five gateway nodes (Songkhla, Suratthani, Nakhon Si Thammarat, Trang and Chumporn) showed promise with regard to GHG emissions reduction. The restructure of the distribution network to four gateway nodes (Songkhla, Suratthani, Nakhon Si Thammarat and Trang) with new transport route R15 was deemed the optimal cost minimisation solution. Route R15, as mentioned in Chapter 5, is a road-sea intermodal transport route. For this route, cargo is transported by truck from point of origin to the Kantang coastal port terminal before being moved by short-sea shipping to Penang port.

If Thai Rubber policy makers decide to take action in restructuring the distribution and transportation network, they may choose to establish rubber zoning at this level of implementation. The economic benefit of this level of rubber zoning is that costs of rubber products will be reduced by 2.21% from the current industrial price. This is equivalent to 7,052 million Baht or USD235 per year. In terms of environmental benefits, total GHG emissions for rubber products will be 1.07 tons of GHG emissions per ton of product.

Economically competitive rubber zoning areas can be divided into four zones as follows:

- *The Western-South network flow zone comprising:*

  Four provinces: Trang, Pattalung, Krabi and Phuket. The primary rubber products from this network flow zone are sent to the factory in Trang province to produce intermediate rubber products which are then transported through routes R7, R8 and R15.

- *The Eastern-South network flow zone:*

  Nakhon Si thammarat is the only province in this network flow zone. The primary rubber products from this network flow are processed into intermediate rubber products at Nakhon Si Thammarat and subsequently transported through routes R1, R12 and R13.

- *The Upper-South network flow zone:*

  There are four provinces in this network flow zone: Chumporn, Ranong, Suratthani and Phangnga. The primary rubber products from this network flow are sent to Suratthani province and subsequently transported through routes R2, R12 and R14.

- *The Lower-South network flow-zone:*

  There are five provinces in this network flow-zone: Songkhla, Satun, Pattani, Yala and Narathiwat. The products from these provinces are sent to the factory at Songkhla and then transported through routes R2, R3 and R5.

The network flow and each rubber entity's capacity allocation for the economically competitive rubber zoning network flow are presented in Figure 7-4. The economically competitive network flow-zone area is shown in Figure 7-5.

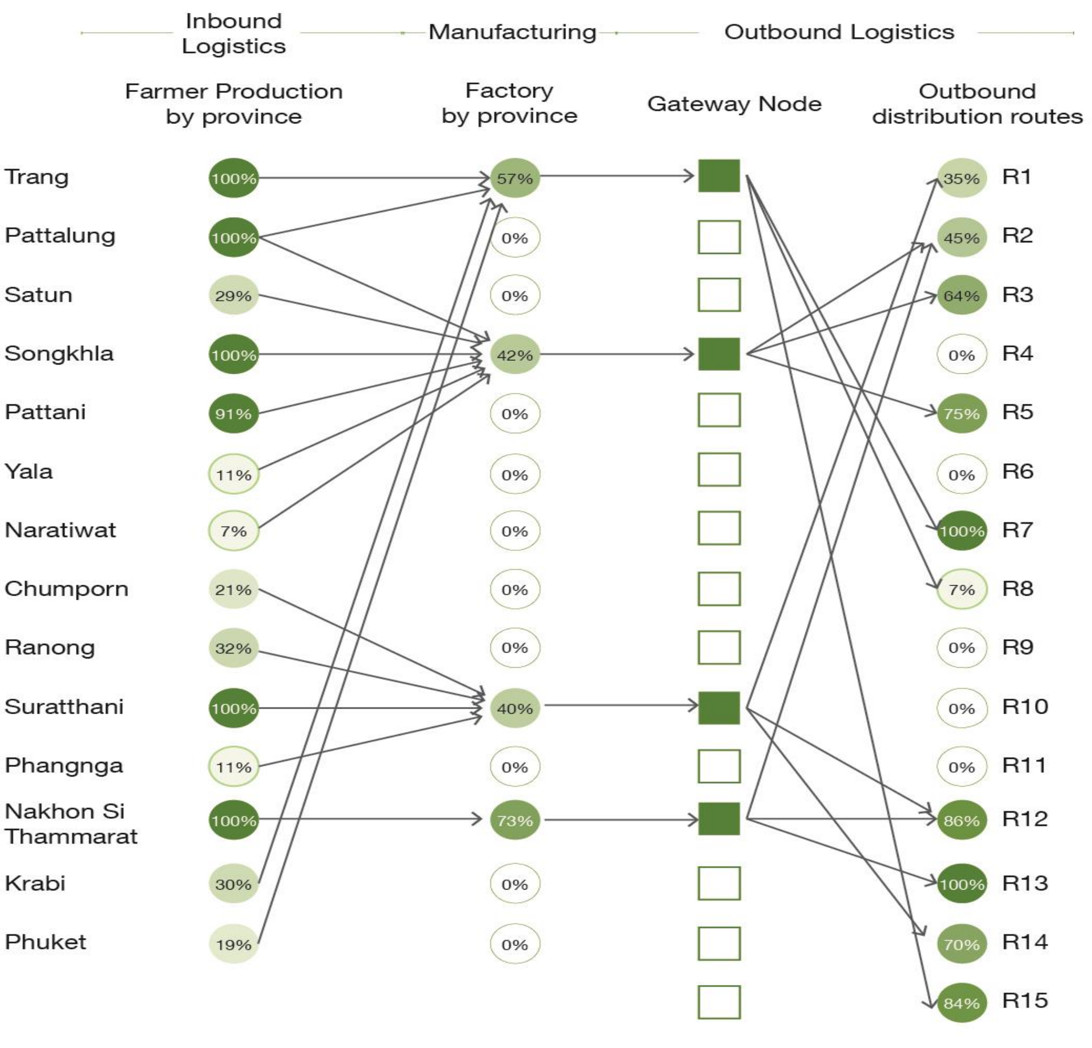

Figure 7-4: The economically competitive rubber zoning network flow- the intermediate level (repeated in figure 5-2)

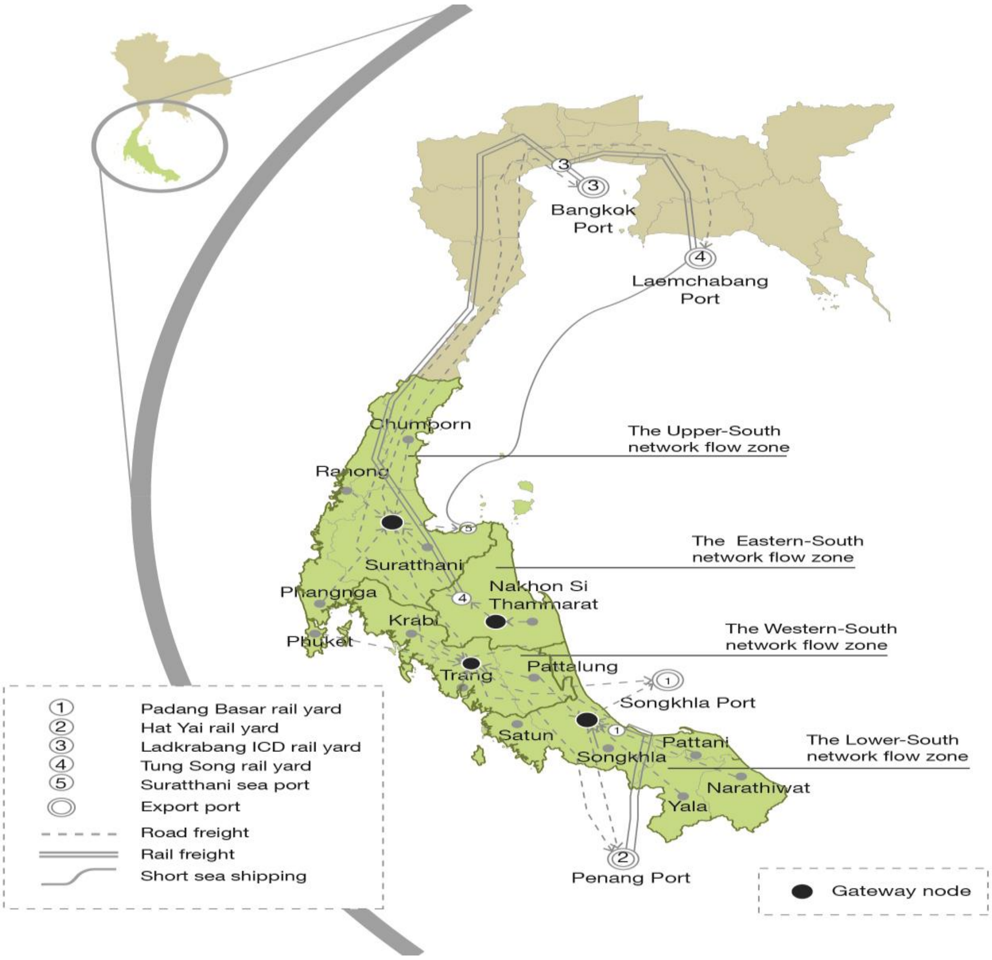

Figure 7-5: The economically competitive network flow-zone area- the intermediate level

With regard to environmental responsibility, the southern area of Thailand rubber's plantations can be divided into five rubber network flow-zones as follows:

- *The Western-South network flow-zone:*

  This network flow-zone comprises Trang and Pattalung provinces. The primary rubber products from this network flow-zone are sent to the factory in Trang province to produce intermediate rubber products which are then transported via route R4.

- *The Eastern-South network flow-zone:*

  The two provinces in this network flow–zone are Suratthani and Phangnga. The primary rubber products from this network flow-zone are processed into intermediate rubber products at Suratthani province and subsequently transported via route R14.

- *The Upper-South network flow-zone:*

  The two provinces of Chumporn and Ranong make up this network flow-zone. Since there is no rubber factory at Chumporn, the primary rubber products in this zone are sent to a factory in Suratthani for processing into intermediate rubber products. The intermediate rubber products are then subsequently transported to their final destinations via transportation routes R1, R2 and R8 through the new gateway node at Chumporn. In the future, policy makers may consider Chumporn province for development as a new gateway node by establishing a rubber factory, general market and intermodal terminal.

- *The Middle-South network flow-zone:*

  Nakhon Si Thammarat is the only province in this network flow-zone. The primary rubber products from this network flow are processed into intermediate rubber products at Nakhon Si Thammarat and subsequently transport through routes R12 and R13.

- *The Lower-South network flow-zone:*

  There are five provinces in this network flow-zone: Songkhla, Satun, Pattani, Yala and Narathiwat. The products from these provinces are sent to the factory at Songkhla and then transported via routes R3 and R5.

The network flow for environmentally friendly rubber zoning and the environmentally friendly network flow-zone areas are shown in Figures 7-6 and 7-7.

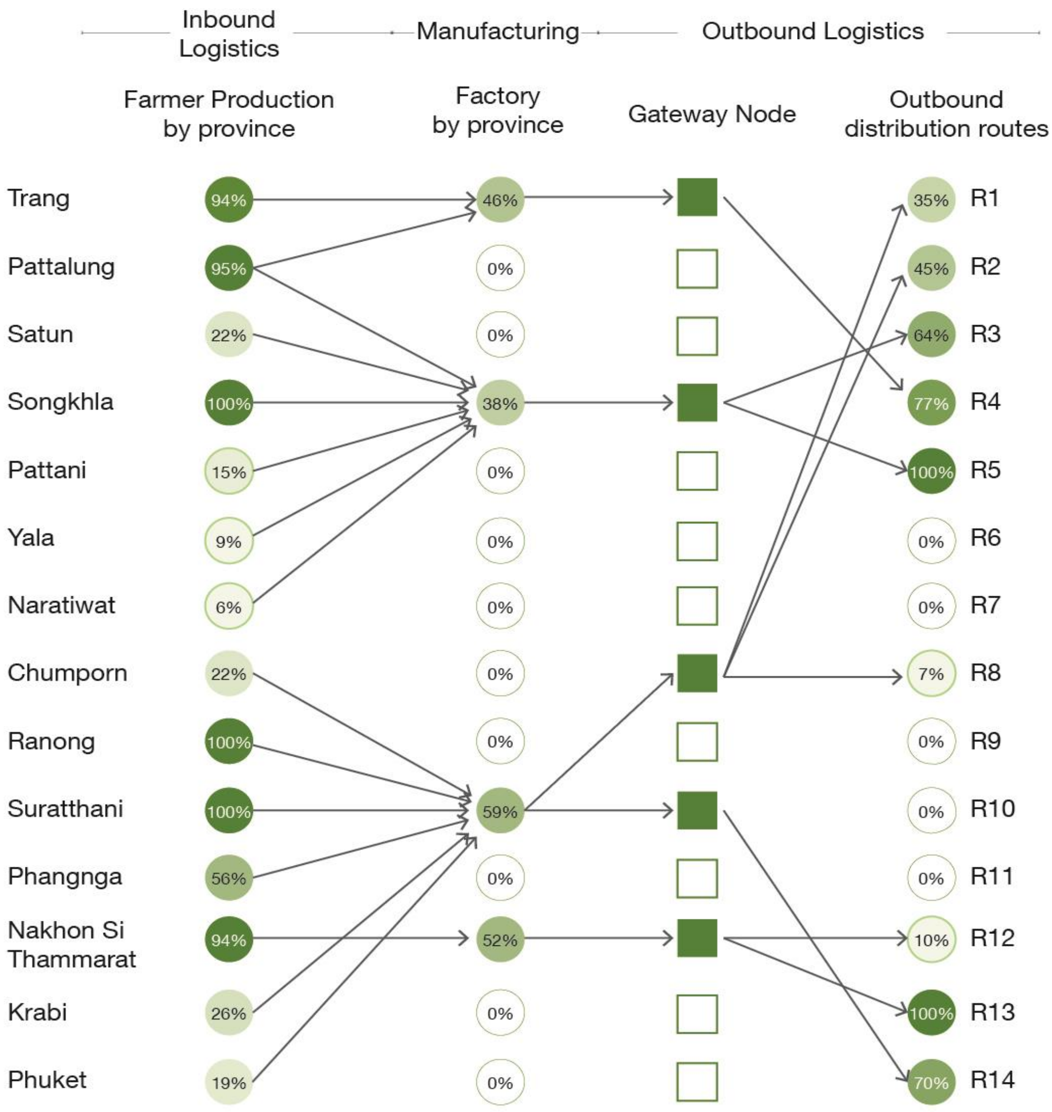

Figure 7-6: The environmentally friendly rubber zoning network flow-the intermediate level (repeated in figure 5-3)

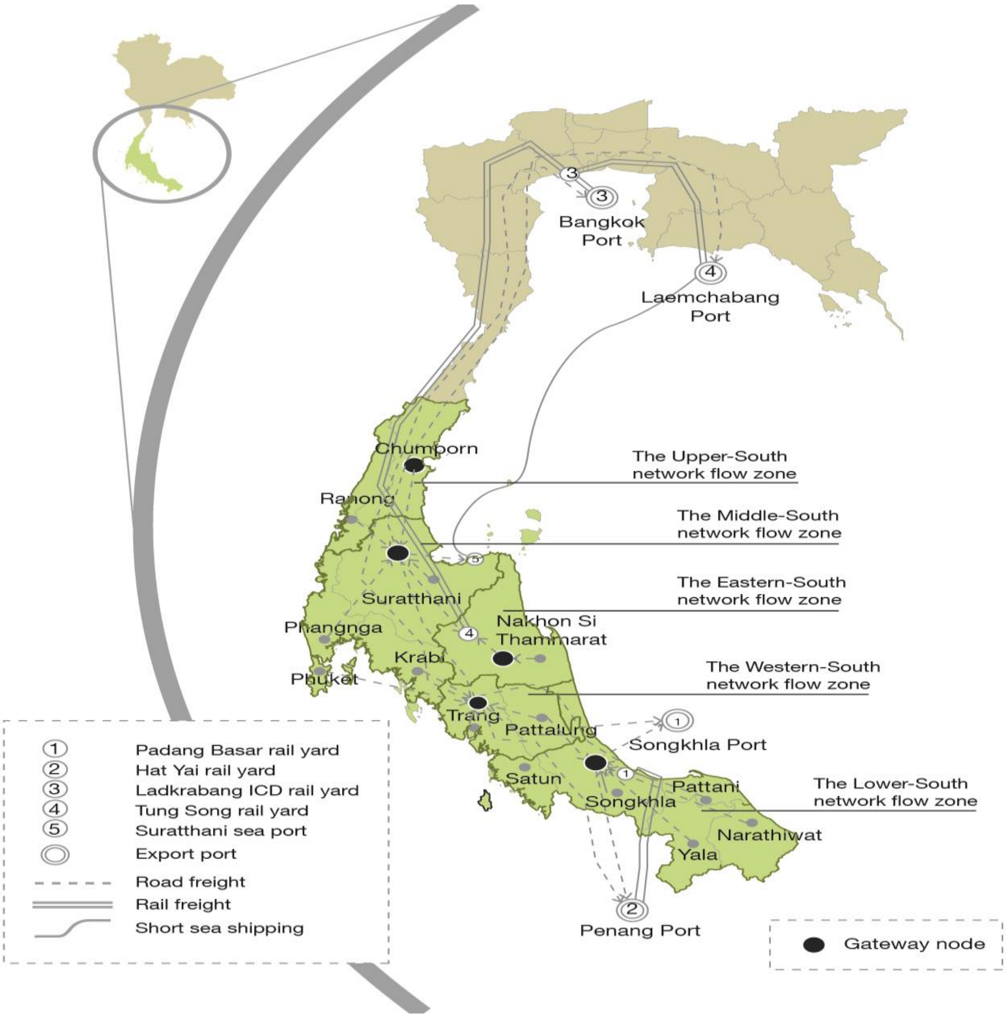

Figure 7-7: The environmentally friendly network flow-zone area- the intermediate level

7.2.3 The trade-off level of rubber zoning implementation

It can be seen from the previous description of two levels of rubber zoning, that the Thai Rubber policy maker must choose between cost objectives and environmental objectives when seeking to improve supply chain management. Consequently, when implementing primary and intermediate level rubber zoning the policy maker must choose between one objective or the other. However, the actual practice of choosing one objective may then significantly jeopardise the other.

The trade-off level of rubber zoning aims to address this issue by providing the set of solutions trade-offs between costs and GHG emissions. The main advantage of the Pareto solution is that it offers a set of trade-offs to assist with the design of the supply chain network, rather than attempting to solve the issue with a single solution. Each point of the Pareto set entails a specific quantity of rubber product flow between the supply chain entities and the transportation mode and route. Therefore, the policy maker can choose the most effective option with regard to preference and applicable policy. Although the choice of a compromise solution entails consideration of preferences and judgement, the solutions are all optimally configured. At this level of implementation, the selection of any solution will require some post-optimal analysis. This is where the model developer must work closely with policy makers regarding the articulation of preferences. In this regard, when analysing trade-off points, the model developer can interpret the solution for the establishment of a rubber zone in such a way that the policy maker can operate the supply chain network according to their selection. The graph in Figure 7-8 illustrates the trade-off solutions between costs and GHG emissions. This graph was previously discussed in Chapter 6 (section 6.4).

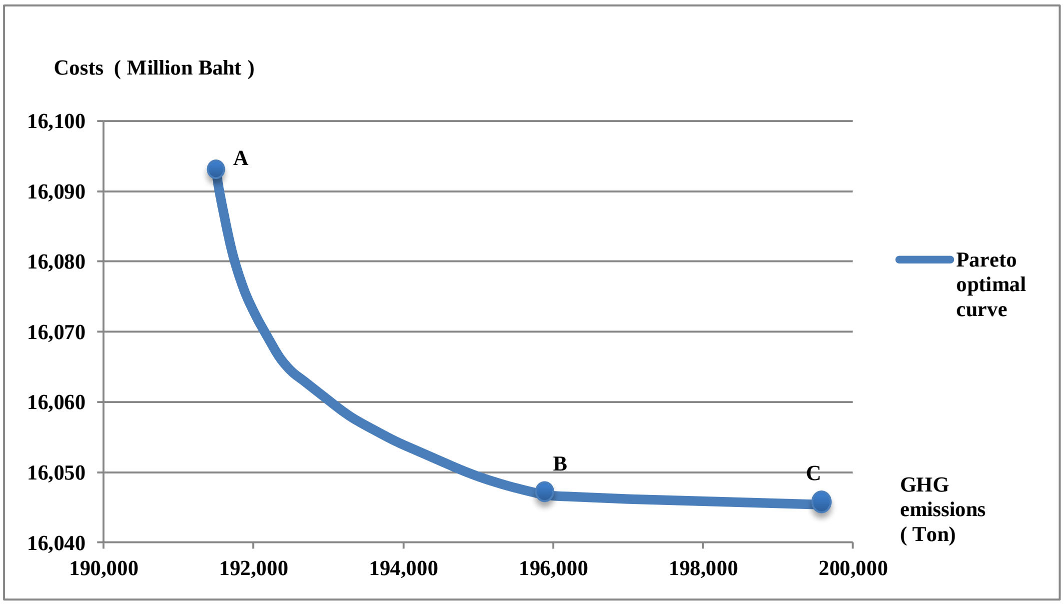

Figure 7-8: Pareto optimal curve (repeated in Figure 6-1)

At this level of rubber zoning implementation, the Pareto optimal solution can also help identify opportunities to incorporate environmental management strategies into the Thai Rubber industry. The Pareto curve presented in Figure 7-8 can be used as a tool to estimate the potential gain in environmental improvements compared to the costs of obtaining this gain. For instance, the solution at point B, as one possible trade-off solution, shows that in order to reduce 1 ton of GHG emissions from the extreme GHG emissions minimisation solution at point A, the compromise is an increase in costs of 0.01 million Baht.

In choosing to adopt environmental policies, Thai Rubber policy makers are advised to use the Pareto curve, as it is indicative of the estimated cost of achieving a given environmental goal. It can be seen from the rubber zoning implementation proposal, that the models developed in this thesis are efficient tools for providing basic guidelines regarding the adoption of GSCM practice in the Thai Rubber industry.

To illustrate the post optimal analysis, point B in the Pareto optimal curve (see Figure 7-8) is selected to present the trade-off level rubber zoning implementation. Figure 7-9 presents the network flow and each rubber entity's capacity allocation in order to be economic while being environmental friendly. Moreover, the network flow zone area is shown in Figure 7-10.

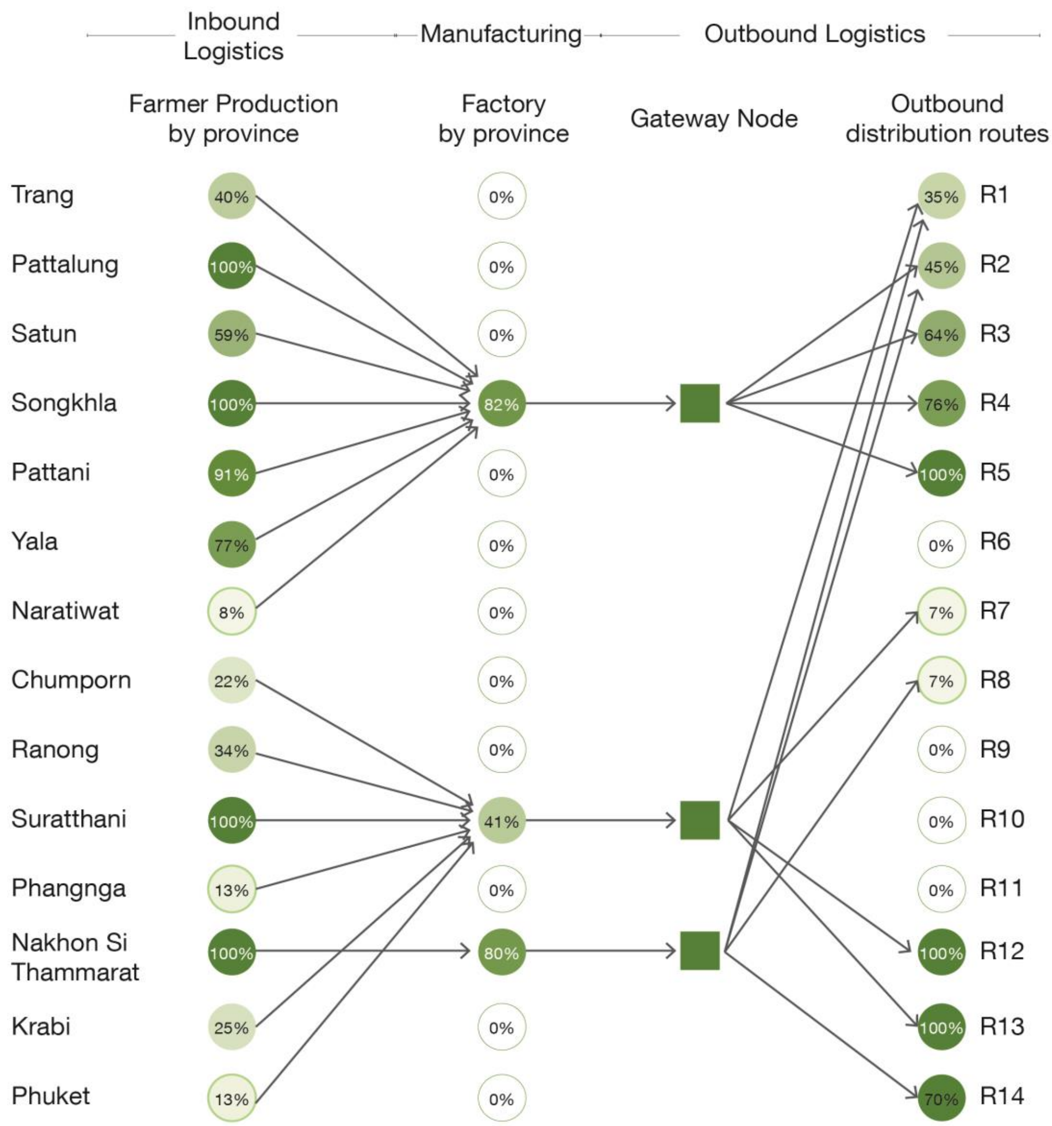

Figure 7-9: The trade-off of economic and environmentally friendly rubber zoning network flow – the trade-off level

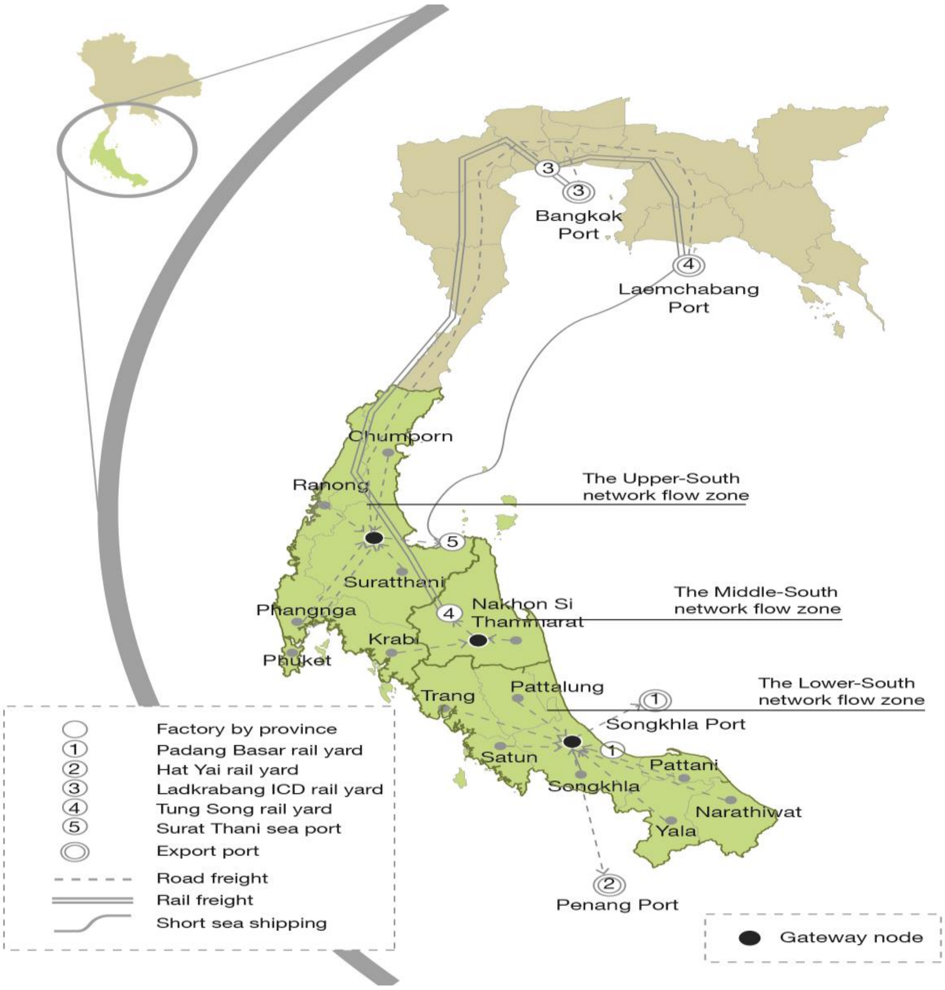

Figure 7-10: The trade-off of economic and environmentally friendly network flow-zone area- the trade-off level

The trade-off level rubber zoning can be divided into three network flow zone areas as follows:

- *The Lower-South network flow zone:*

  This zone comprises seven provinces (Trang, Pattalung, Satun, Songkhla, Pattani, Yala and Narathiwat). The primary rubber products from this network are sent to the factory in the Songkhla province to produce intermediate rubber products which are then transported through routes R2, R3, R4 and R5.

- *The Middle-South network flow zone:*

  There is one province in this network flow zone: Nakhon Si Thammarat. The primary rubber products from this network flow are processed in Nakhon Si Thammarat province then subsequently transported through routes R1, R2, R8 and R14.

- *The Upper-South network flow zone:*

  There are six provinces in this network flow zone. The provinces in this network flow zone include Suratthani, Chumporn, Ranong, Phangnga, Krabi and Phuket. The products from these provinces are sent to the factory at Suratthani and then transported through routes R1, R7, R12 and R13.

7.3 SUMMARY

In this chapter, the analysis of solutions to better manage the Thai Rubber supply chain were discussed. Three levels of rubber zoning were proposed to manage the Thai Rubber supply chain. At each level of rubber zoning, the network flow-zone area was identified, along with network linkages and allocations for farmer and factory production capacity. The primary level of rubber zoning implementation optimised the current industrial practice supply chain, while the intermediate level proposal took a step forward in restructuring the distribution and transportation network. In addition, both levels of rubber zoning were proposed from a single-objective optimisation perspective. Thus, in practice the policy maker must select the objective to implement. At the "trade-off" level, economic and environmental objectives were simultaneously optimised. At this level, post-optimal analysis is required to articulate the policy maker's preferences and judgement. At this final stage, the analysis of Pareto optimal solutions provides valuable insights such as environmental management indicators for the Thai Rubber industry.

CHAPTER 8

CONCLUSIONS AND FUTURE RESEARCH

The purpose of this thesis is to develop a decision-support model for the Thai Rubber policy maker. This would allow more effective management of the Thai Rubber supply chain with regard to economic gain and environmental responsibility. In order to achieve this goal, the Green Supply Chain Management modelling approach was adopted. Linear programming single objective optimisation and linear multi- objective optimisation were chosen for model development and formulation.

Hence, the research supporting this thesis was conducted as per Figure 8-1 below:

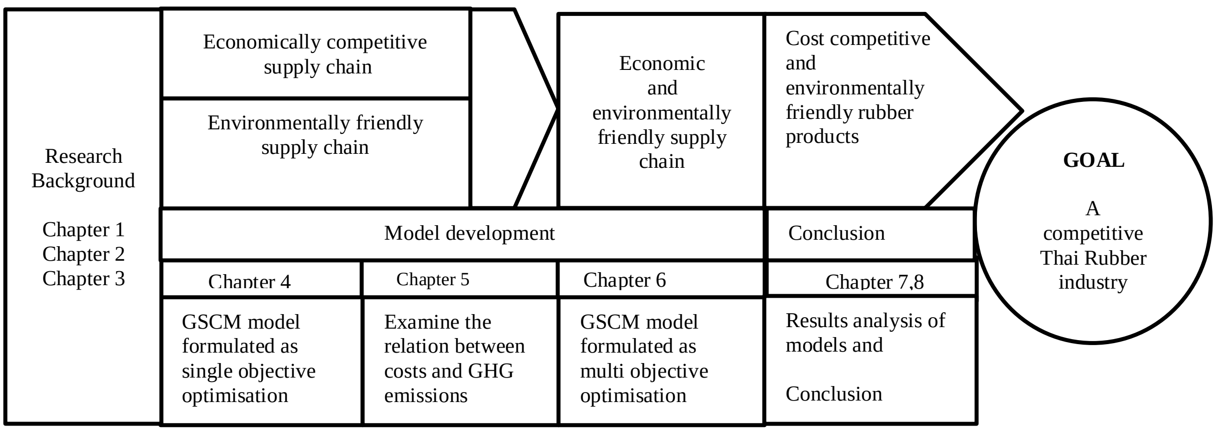

Figure 8-1: Thesis roadmap (repeated from Figure 1-1)

The main findings and contributions from each chapter in this thesis are summarised as follows:

8.1 FINDINGS AND CONTRIBUTIONS

Chapter 2 presented an overview of the Thai Rubber industry which aimed to set the scene for the chapters that followed. This chapter was concerned with the major elements of the Thai Rubber supply chain and related processes that incurred costs and produced GHG emissions. Overall, the main contributions from this chapter are as follows: the presentation of a global view of the rubber industry in terms of supply, demand and price (Section 2.2); the importance of the Thai Rubber industry to the Thai economy is highlighted (Section 2.3). Moreover, the common definition of each rubber supply chain entity and its relevant process; costs and GHG emissions from the Thai Rubber supply chain were investigated and presented in sections 2.4 and 2.5 respectively. To the best of the author’s knowledge, this thesis is the first to calculate GHG emissions from the rubber supply chain. In section 2.5.2 the rubber supply chain GHG emissions components were reviewed and summarised in the GHG emissions calculation framework for the Thai Rubber supply chain (Figure 2-11).

In Chapter 3, published journal articles and studies regarding the GSCM principle, modelling and applications were reviewed to provide the theoretical background to the thesis. This chapter reviewed the current state of the following approaches: (1) Supply Chain Management (SCM) in section 3.2; (2) Green Supply Chain Management (GSCM) in section 3.3; (3) modelling approaches in GSCM in section 3.4 and (4) mathematical approaches in the GSCM model in section 3.5. While this chapter contributed to providing a review of the GSCM relevance principle, it also indicated research field gaps in GSCM modelling approaches and recommended mathematical techniques for research into the Thai Rubber supply chain in section 3.4.4 and 3.5.4.

Chapter 4 provided the modelling groundwork for the development of a GSCM model for the Thai Rubber industry. In this chapter, the GSCM model was formulated in terms of linear programming single-objective optimisation. The objective function of minimising total costs represented economic performance, whilst the minimising of total GHG emissions indicated environmental performance. The contributions in this chapter were at the modelling level where GSCM modelling was captured, and at the industrial level where the Thai Rubber industry would benefit from using this model for cost savings and GHG emission reductions. The contributions are as follows:

Modelling level contributions:

- This chapter provided the Thai Rubber supply chain model framework (Figure 4-1) illustrating major supply chain entities. The framework can be applied to other research into the supply chain for the Thai Rubber industry.
- The GSCM model, formulated as a linear programming, and an optimised single objective (Section 4.4), was presented.
- Thai Rubber product costs and GHG emissions were calculated (section 4.7.1 and 4.7.2).
- The optimal network flow of costs and GHG emissions minimisation is presented (Figure 4-6 and 4-7).

Industrial level contributions:

- This chapter provided the decision-support tools to assist the Thai Rubber industry in improving rubber products costs by 1.56%, relative to current industrial practice. This is equivalent to a potential saving of USD138 million per year (section 4.7.1). The GHG emissions for rubber products were calculated at 1.08 tons of GHG emissions per ton of product (Section 4.7.2)

Chapter 5 was designed to extend the observations and indications from the results of Chapter 4. This chapter examined the impact of transportation and distribution restructuring on costs and GHG emissions. The assessment was presented through the scenario analysis in sections 5.3 and 5.4. The insights obtained from this chapter aim to contribute to the literature and the development of policy in the Thai Rubber industry. The findings should assist in decision-making with regard to transportation and distribution development as follows:

Literature contributions:

- The scenario analysis of transportation in this chapter contributed to argue the claim made by Wasusri and Chaichompoo (2008) along with earlier research into the Thai Rubber supply chain by Kritchanchai (2009). The suggestion was to promote rail freight and short-sea shipping lines as a strategy for competitiveness in economic performance. This chapter found that the development of outbound transportation for rail freight and short-sea shipping would not result in worthwhile economic benefits (Table 5-1).
- The scenario analyses of distribution network restructuring supported the research of Harris et al. (2010), that the optimum design based on costs does not necessarily equate to optimum solutions based on GHG emissions (Table 5-3).

Industrial level contributions:

- With regard to economic benefits, this chapter pointed out that distribution network restructuring provides more worthwhile benefits to the industry than developments in transportation. The industry has the potential to save 2.13% or USD 228 million by restructuring the distribution network to five gateway nodes (Table5-3)
- From an environmental standpoint, this chapter’s findings show that the restructuring of the rail freight service resulted in a significant positive impact with a potential GHG emission reduction of up to 5.5% (Table 5-2).

Finally, the modified model with the distribution network restructuring analysis showed that costs and GHG emission optimal results for outbound distribution conflicted when transportation and distribution were restructured.

Chapter 6 aimed to address the limitations of single-objective optimisation developed in Chapter 4 by adopting the multi-objective optimisation model (with particular focus on the bi-objective case) into the Thai Rubber supply chain. This model was developed from the basis-modelling framework in Chapter 4. The ε-constraint method was adopted to calculate the Pareto set of solutions for problems in the Thai Rubber supply chain in order to simultaneously minimise total costs and total GHG emissions. Each solution within the set represented options for the flow of the quantity of rubber product between supply chain entities and transportation modes and routes. In addition, to illustrate the trade-off curves for the benefit of policy makers, the transportation and distribution restructure scenarios were performed. The main contributions in this chapter are to modelling and to policy support at the industrial level:

Modelling level contributions:

- GSCM model formulated as a linear multi-objective optimisation model presented in section 6.2.
- The Pareto curve (Figure 6-1) which clearly demonstrates the trade-offs between total costs and total GHG emissions. This curve highlights that improvement in cost reductions for the Thai Rubber supply chain is only possible by making a compromise with regard to higher GHG emissions.

Industrial level contributions:

- Decision support tools to estimate the potential gain in environmental improvements compared with the costs to obtain this gain. The most promising solutions discussed in section 6.4 indicated that the cost of reducing 1 ton of GHG emissions in the Thai Rubber supply chain, would be an additional 0.01 million Baht (added to the original cost).

- The Pareto curve of the transportation scenarios (Figure 6-2 in section 6.5.1) concluded that increases in rail freight operations would produce less GHG emissions in the supply chain. The distribution scenario Pareto curves (Figures 6-3, 6-4 in section 6.5.2) shows that at the same GHG emissions level, the more gateway nodes, the lower the cost.

Policy support given by the Pareto optimal solution generated in this chapter was discussed in Chapter 7. Furthermore, Chapter 6 extended the basis-modelling developed earlier in chapter 4 by addressing the model's weaknesses and improving its capability.

Chapter 7 discussed the results analyses from Chapters 4, 5 and 6 with regard to improved policy implementation for the Thai Rubber supply chain. The establishment of rubber zoning was proposed through three levels of implementation according to the current readiness of industry and ease of implementation. This is the main contribution in this chapter. It aimed to address the current industry weaknesses to manage the unstructured supply chain. Rubber zoning can be used to support any policy related to the rubber industry. This include: land use control for new plantations, rubber manufacturer zoning, number of traders in each region and transport infrastructure investment. The three levels of rubber zoning establishment was proposed in this chapter are as follows:

- Primary level rubber zoning implementation. At this stage of rubber zoning, the economically competitive and environmentally friendly rubber zoning network flow was presented (Figure 7-1 and 7-2) along with detail of each network flow (Figure 7-3)
- Intermediate level rubber zoning implementation was discussed in section 7.2.2. The economically competitive rubber zoning can be divided into four zones (Figure 7-4 and 7-5) while the environmentally

competitive network flow zone can be divided into five rubber network flow-zones (Figure 7-6 and 7-7).

- Trade-off rubber zoning implementation. In this stage of rubber zoning proposal, the Pareto curves was shown as a set of optimal solutions from which the policy maker can choose the most effective option with regard to preference and applicable policy (Figure 7-8). In addition, policy support proposals regarding environmental issues (from Figure 7-8) were discussed. The aim here was to guide the Thai Rubber policy maker as how to investigate the possibilities for the private sector to initiate green awareness. The trade-offs of economic competitive and environmentally friendly network flow and rubber zoning was also presented. (Figure 7-9 and Figure 7-10)

In summary, this thesis demonstrates how to develop a decision-support model for the Thai Rubber industry to assist in managing the Thai Rubber supply chain such that it may achieve economic gain whilst remaining environmentally friendly. In order to achieve this goal, a Green Supply Chain Management (GSCM) modelling approach was adopted. Linear Programming single objective optimisation and linear multi-objective optimisation was chosen for the model development and formulation. The model was formulated by incorporating information regarding the production, distribution, and transportation of rubber products in such a manner that total costs and total GHG emissions would be minimised both separately and simultaneously. It thus addressed the research objectives discussed in section 1.2.

The initial stage of this thesis developed the GSCM model by formulating costs and GHG emissions as two single objective functions. Its aim was to provide a comprehensive understanding of the basic elements of the model in relation to costs and GHG emissions. Once the model was developed and the results analysed, the relationship between costs and GHG emissions in the Thai Rubber supply chain was examined. Then, the second model formulated the multi objective linear programming optimisation model for the Thai Rubber supply chain. The objective was to provide a trade-offs solutions between costs and GHG emissions. From the set of alternative solutions provided, the decision maker can now investigate and select the supply chain network design that most satisfies their preferences. Furthermore, this thesis has proposed the establishment of rubber zoning to manage the unstructured Thai Rubber supply chain, which has been discussed earlier.

However, this thesis has several limitations. The next section discusses this thesis's limitation and a scope of future research to address these limitations.

8.2 FUTURE RESEARCH

Several avenues of future research remain open with respect to the expansion and improvement of the GSCM model for the Thai Rubber industry developed in this thesis.

Firstly, the study areas in this thesis did not cover rubber plantations and production in the whole of Thailand. Even though rubber production areas are mainly located in Southern Thailand, future research may extend the study area to cover other rubber plantation regions in Thailand, such as the North, North-Eastern and Eastern areas. The supply chain model framework and mathematical formulation in this thesis is general enough to be easily extended to any other rubber supply chain.

It can be noticed from the study by Jawjit, Kroeze and Rattanapan (2010) that GHG emissions for rubber products from the North, North-Eastern and Eastern rubber plantations are significantly higher than those from the Southern region. This is due to the carbon stock from those land-converted areas (see Table 2-2). Hence, future research may take this observation into account when investigating total GHG emissions from the rubber supply chain in those regions. It may also be advisable to check total GHG emissions for rubber products produced in different parts of Thailand for purposes of accuracy and comparison.

The framework for the Thai Rubber supply chain was used to investigate the impact of activities on costs and GHG emissions through the forward supply chain. The study examined both primary and intermediate rubber products which are generally transported as bulk deliveries. As waste and recycling were not examined, future research may investigate this with regard to final rubber products such as medical gloves or vehicle tyres. This could be undertaken by incorporating reverse logistics into the design of the GSCM model.

Finally, the GSCM model developed here provides an effective tool for minimising total costs and total GHG emissions in the Thai Rubber supply chain both separately and simultaneously. However, it fails to take into account the uncertainty inherent in real-world rubber production and distribution networks. Therefore, to address this limitation, future research input uncertainties such as demand, supply and price may be considered. For instance, uncertain rubber production capacities and yields per farm, rubber demand and rubber prices may be incorporated into the model as uncertain parameters.

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APPENDIX

OPL SCRIPT FOR COST MINIMISATION MODEL FORMULATIO AND PROBLEM SOLVING USING C-PLEX OPL STUDIO 12.3

```
/*********************************************
* OPL 12.4 Model
* Author: 14406058
* Creation Date: 13/08/2012 at 12:28:14 PM
*********************************************/
/* Cost model */

{string} Products = ...;
{string} FarmSize = ...;
{string} T1 = ...;
{string} TradGroup = ...;
int NFactories = ...;
range Factories = 1..NFactories;
{string} EndProducts = ...;

{string} DistNode = ...;
{string} Destinations = ...;
{string} Provinces = ...;
{string} TransRoute = ...;

float Distance[Provinces][Provinces]=...;

float Production[FarmSize][Provinces] = ...;
float FarmerProdCost[FarmSize][Products] = ...;
float TransCostFarmSize[FarmSize][T1][TradGroup] = ... ;

float TradGroupCap[TradGroup][Products][Provinces] = ...;
float TradGroupCost[TradGroup][Products]= ... ;
float TransCostTradGroup[Provinces][TradGroup][Factories] = ...  ;

float FactCap[Factories][EndProducts] = ...;
float FactProdCost[Factories][EndProducts]= ... ;
float TransCostFactDistNode[Factories][DistNode] = ... ;

float DisNodeCap[DistNode] = ...;
float TransDistNodeTransRouteCost[DistNode][TransRoute]= ... ;
float TransRouteCap[TransRoute] = ...;
float TransRouteCost[TransRoute] = ...;
     float TransRouteDestinationsCost[TransRoute][Destinations] = ... ;
float Demand[Destinations][EndProducts] = ...;

dvar float+ X[Provinces,FarmSize,Products,T1,TradGroup];
     dvar float+ Y[Provinces,TradGroup,Factories,EndProducts,DistNode];
dvar float+ Z[EndProducts,DistNode,TransRoute,Destinations];

dexpr float Objective =
     sum(i in Provinces,s in FarmSize,p in Products,t in T1,g in
     TradGroup)(X[i,s,p,t,g]*(FarmerProdCost[s,p]+TransCostFarmSize[s,t,g]
     +TradGroupCost[g,p])) + sum(i in Provinces,g in TradGroup,f in
```

```
     Factories,e in EndProducts,a in
     DistNode)(Y[i,g,f,e,a]*(TransCostTradGroup[i,g,f]+FactProdCost[f,e]+T
     ransCostFactDistNode[f,a])) + sum(e in EndProducts,a in DistNode, b
     in TransRoute,d in Destinations)
     (Z[e,a,b,d]*(TransDistNodeTransRouteCost[a,b]+TransRouteCost[b]+Trans
     RouteDestinationsCost[b,d]));

constraint CT1[Provinces][FarmSize];
constraint CT2[Provinces][TradGroup][Products];
constraint CT3[Factories][EndProducts];
constraint CT4[DistNode];
constraint CT5[TransRoute];
constraint CT6[Destinations][EndProducts];
constraint CT7[Provinces][TradGroup];
constraint CT8[EndProducts][DistNode];

minimize Objective;

subject to {

     forall(i in Provinces, s in FarmSize) {
         CT1[i][s]: sum( p in Products,t in T1,g in TradGroup)
     X[i,s,p,t,g] <=Production[s,i];
 }

     forall(i in Provinces, g in TradGroup, p in Products) {
         CT2[i][g][p] : sum(s in FarmSize,t in T1) X[i,s,p,t,g] <=
     TradGroupCap[g,p,i];
 }

     forall(f in Factories,e in EndProducts) {
         CT3[f][e] : sum(i in Provinces,g in TradGroup,a in DistNode)
     Y[i,g,f,e,a] <= FactCap[f,e];
 }

     forall(a in DistNode) {
         CT4[a] : sum(i in Provinces,g in TradGroup,f in Factories,e in
     EndProducts) Y[i,g,f,e,a] <= DisNodeCap[a];
 }

     forall(b in TransRoute) {
         CT5[b] : sum(e in EndProducts,a in DistNode, d in Destinations)
     Z[e,a,b,d] <= TransRouteCap[b];
 }

   forall(d in Destinations,e in EndProducts) {
         CT6[d][e]: sum(a in DistNode, b in TransRoute) Z[e,a,b,d] ==
     Demand[d,e];

 }

     forall (i in Provinces,g in TradGroup){
     CT7[i][g]: sum(s in FarmSize,p in Products,t in T1) X[i,s,p,t,g] ==
     sum(f in Factories,e in EndProducts,a in DistNode)Y[i,g,f,e,a];
 }

     forall (e in EndProducts, a in DistNode){
         CT8[e][a]: sum(i in Provinces,g in TradGroup,f in
     Factories)Y[i,g,f,e,a] == sum(b in TransRoute,d in
     Destinations)Z[e,a,b,d];
 }
```

```
      ((sum(i in Provinces,g in TradGroup,f in Factories,a in DistNode)
      Y[i,g,f,"STR",a])*0.2+(sum(i in Provinces,g in TradGroup,f in
      Factories,a in DistNode) Y[i,g,f,"RSS",a])) == (sum(i in Provinces,s
      in FarmSize, t in T1,g in TradGroup) X[i,s,"US",t,g]);
      ((sum(i in Provinces,g in TradGroup,f in Factories,a in DistNode)
      Y[i,g,f,"STR",a])*0.8) == (sum(i in Provinces,s in FarmSize, t in
      T1,g in TradGroup) X[i,s,"CL",t,g]);
      ((sum(i in Provinces,g in TradGroup,f in Factories,a in DistNode)
      Y[i,g,f,"LCT",a])) == (sum(i in Provinces,s in FarmSize, t in T1,g
      in TradGroup) X[i,s,"LX",t,g]);
      }

      execute
{
 for (i in Provinces){
   for (sin FarmSize){
 writeln(CT1[i][s].dual);
     }
}
}
     execute
{
 for (i in Provinces){
   for (g in TradGroup){
     for (p in Products){
 writeln(CT2[i][g][p].dual);
}
}
}
}
execute
{
 for (f in Factories){
   for (e in EndProducts){
 writeln(CT3[f][e].dual);
}
}
}
execute
{
 for (a in DistNode){
     writeln(CT4[a].dual);
}
}
execute
{
 for (b in TransRoute){
     writeln(CT5[b].dual);
}
}
execute
{
 for (d in Destinations){
   for (e in EndProducts){
 writeln(CT6[d][e].dual);
}
}
}
execute
{
```

```
 for (i in Provinces){
   for (g in TradGroup){
 writeln(CT7[i][g].dual);
}
}
}
execute
{
 for (e in EndProducts){
   for (a in DistNode){
 writeln(CT8[e][a].dual);
}
}
}


 /*********************************************
     * OPL 12.4 Data
     * Author: 14406058
     * Creation Date: 13/08/2012 at 12:28:14 PM
 *********************************************/
 /* Cost model */

     Provinces = { Trang, Pattalung, Satun, Songkhla, Pattani, Yala,
     Narathiwat,Chumporn, Ranong, Surathani, Phangnga, Nakhon, Krabi,
     Phuket};
Products = { US, CL, LX };
FarmSize = { S, M, L };
T1 = { "4W", "10W" };
TradGroup = { DL, GM, CO };
NFactories = 14;
EndProducts = { STR, RSS, LCT };
DistNode = {D1,D2,D3};

TransRoute = {R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14};

Destinations = {CTS, DOS, SKP, PNG, BKK, LCB};

Distance =[
[45,54,116,117,199,217,275,331,289,179,155,106,95,137],
[54,45,111,75,154,178,233,336,306,189,195,92,138,188],
[116,111,45,88,137,135,195,443,404,292,266,202,205,232],
[117,75,88,45,82,105,160,401,378,259,268,154,209,254],
[199,154,137,82,45,38,233,464,449,330,349,224,291,336],
[217,178,135,105,38,45,61,498,480,360,371,255,311,351],
[275,233,195,160,80,61,45,539,528,408,428,303,369,411],
[331,336,443,401,464,498,539,45,83,153,237,246,272,303],
[289,306,404,378,449,480,528,83,45,119,167,225,214,233],
[179,189,292,259,330,360,408,153,119,45,113,105,126,171],
[155,195,266,268,349,371,428,237,167,113,45,158,61,67],
[106,92,202,154,224,255,303,246,225,105,158,45,123,183],
[95,138,205,209,291,311,369,272,214,126,61,123,45,60],
[137,188,232,254,336,351,411,303,233,171,67,183,60,45]
];



Production = [
     [28144, 12109, 6602, 31304, 6375, 22492, 20777, 11484, 4325, 39782,
     16594, 31005, 13080, 1831],
```

```
     [1513, 651, 355, 1683, 343, 1209, 1117,617, 233, 2139, 892, 1667,
     703, 98],
     [605, 260, 142, 673, 137, 484, 447, 247, 93, 856, 357, 667, 281, 39]
];

FarmerProdCost = [
[81480, 69260, 68440],
[77406, 65797, 65018],
[69258, 55927, 58174]
];

TransCostFarmSize =[
[[600,560,580],
[650,650,650]],
[[600,560,580],
[600,560,580]],
[[560,600,580],
[520,550,540]]
];

TradGroupCap = [
[

     [10705,5174,1070,17930,2230,6601,5602,8653,5977,15076,3211,12043,4282
     ,1427],
     [16057,7761,1606,26896,3345,9902,8430,12979,8965,22614,4817,18064,642
     3,2141],
     [2141,1035,214,3586,446,1320,1124,1731,1195,3015,642,2409,856,285]
],
[
[0,0,0,3616,0,0,0,0,0,3000,0,3300,0,0],
[0,0,0,0,0,0,0,0,0,0,0,0,0,0],
[0,0,0,1004,0,0,0,0,0,1000,0,1000,0,0]
],
[
[0,0,0,0,0,0,0,0,0,0,0,0,0,0],
[0,0,0,0,0,0,0,0,0,0,0,0,0,0],
     [3000,3938,1313,5063,188,844,281,1031,281,3094,1313,7125,2438,94]
]
];

TradGroupCost =[
[600,600,600],
[560,560,560],
[580,580,580]
];

TransCostTradGroup = [
[
     [3060,3672,7888,7956,13532,14756,18700,22508,19652,12172,10540,7208,6
     460,9316],
     [2970,3564,7656,7722,13134,14322,18150,21846,19074,11814,10230,6996,6
     270,9042],
     [2880,3456,7424,7488,12736,13888,17600,21184,18496,11456,9920,6784,60
     80,8768]
],
[
     [3672,3060,7548,5100,10472,12104,15844,22848,20808,12852,13260,6256,9
     384,12784],
     [3564,2970,7326,4950,10164,11748,15378,22176,20196,12474,12870,6072,9
     108,12408],
```

```
        [3456,2880,7104,4800,9856,11392,14912,21504,19584,12096,12480,5888,88
        32,12032]
    ],
    [
        [7888,7548,3060,5984,9316,9180,13260,30124,27472,19856,18088,13736,13
        940,15776],
        [7656,7326,2970,5808,9042,8910,12870,29238,26664,19272,17556,13332,13
        530,15312],
        [7424,7104,2880,5632,8768,8640,12480,28352,25856,18688,17024,12928,13
        120,14848]
    ],
    [
        [7956,5100,5984,3060,5576,7140,10880,27268,25704,17612,18224,10472,14
        212,17272],
        [7722,4950,5808,2970,5412,6930,10560,26466,24948,17094,17688,10164,13
        794,16764],
        [7488,4800,5632,2880,5248,6720,10240,25664,24192,16576,17152,9856,133
        76,16256]
    ],
    [
        [13532,10472,9316,5576,3060,2584,15844,31552,30532,22440,23732,15232,
        19788,22848],
        [13134,10164,9042,5412,2970,2508,15378,30624,29634,21780,23034,14784,
        19206,22176],
        [12736,9856,8768,5248,2880,2432,14912,29696,28736,21120,22336,14336,1
        8624,21504]
    ],
    [
        [14756,12104,9180,7140,2584,3060,4148,33864,32640,24480,25228,17340,2
        1148,23868],
        [14322,11748,8910,6930,2508,2970,4026,32868,31680,23760,24486,16830,2
        0526,23166],
        [13888,11392,8640,6720,2432,2880,3904,31872,30720,23040,23744,16320,1
        9904,22464]
    ],
    [
        [18700,15844,13260,10880,5440,4148,3060,36652,35904,27744,29104,20604
        ,25092,27948],
        [18150,15378,12870,10560,5280,4026,2970,35574,34848,26928,28248,19998
        ,24354,27126],
        [17600,14912,12480,10240,5120,3904,2880,34496,33792,26112,27392,19392
        ,23616,26304]
    ],
    [
        [22508,22848,30124,27268,31552,33864,36652,3060,5644,10404,16116,1672
        8,18496,20604],
        [21846,22176,29238,26466,30624,32868,35574,2970,5478,10098,15642,1623
        6,17952,19998],
        [21184,21504,28352,25664,29696,31872,34496,2880,5312,9792,15168,15744
        ,17408,19392]
    ],
    [
        [19652,20808,27472,25704,30532,32640,35904,5644,3060,8092,11356,15300
        ,14552,15844],
        [19074,20196,26664,24948,29634,31680,34848,5478,2970,7854,11022,14850
        ,14124,15378],
        [18496,19584,25856,24192,28736,30720,33792,5312,2880,7616,10688,14400
        ,13696,14912]
    ],
    [
```

```
    [12172,12852,19856,17612,22440,24480,27744,10404,8092,3060,7684,7140,
    8568,11628],
    [11814,12474,19272,17094,21780,23760,26928,10098,7854,2970,7458,6930,
    8316,11286],
    [11456,12096,18688,16576,21120,23040,26112,9792,7616,2880,7232,6720,8
    064,10944]
],
[
    [10540,13260,18088,18224,23732,25228,29104,16116,11356,7684,3060,1074
    4,4148,4556],
    [10230,12870,17556,17688,23034,24486,28248,15642,11022,7458,2970,1042
    8,4026,4422],
    [9920,12480,17024,17152,22336,23744,27392,15168,10688,7232,2880,10112
    ,3904,4288]
],
[
    [7208,6256,13736,10472,15232,17340,20604,16728,15300,7140,10744,3060,
    8364,12444],
    [6996,6072,13332,10164,14784,16830,19998,16236,14850,6930,10428,2970,
    8118,12078],
    [6784,5888,12928,9856,14336,16320,19392,15744,14400,6720,10112,2880,7
    872,11712]
],
[
    [6460,9384,13940,14212,19788,21148,25092,18496,14552,8568,4148,8364,3
    060,4080],
    [6270,9108,13530,13794,19206,20526,24354,17952,14124,8316,4026,8118,2
    970,3960],
    [6080,8832,13120,13376,18624,19904,23616,17408,13696,8064,3904,7872,2
    880,3840]
],
[
    [9316,12784,15776,17272,22848,23868,27948,20604,15844,11628,4556,1244
    4,4080,3060],
    [9042,12408,15312,16764,22176,23166,27126,19998,15378,11286,4422,1207
    8,3960,2970],
    [8768,12032,14848,16256,21504,22464,26304,19392,14912,10944,4288,1171
    2,3840,2880]
]
];

FactCap = [
[16783,16783,50348],
[0,0,0],
[0,0,0],
[43700,50983,50983],
[0,0,0],
[0,0,0],
[0,0,0],
[0,0,0],
[0,0,0],
[80764,40382,40382],
[0,0,0],
[32416,10805,10805],
[0,0,0],
[0,0,0]
];
FactProdCost = [
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
```

```
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800],
[3410,3000,2800]
];

TransCostFactDistNode = [
[11700,17900,10600],
[7500,18900,9100],
[8800,29200,20200],
[4500,25900,15400],
[8200,33000,22400],
[10500,36000,25500],
[16000,40800,30300],
[40100,15300,24600],
[37800,11900,22500],
[25900,6000,10600],
[26800,11300,15800],
[15400,10500,6000],
[20900,12600,12200],
[25400,17100,18300]
];

DisNodeCap = [500000,500000 ,500000];

TransDistNodeTransRouteCost = [
     [2510,2560,1797,2357,2128,8200,8200,2510,2560,8200,8200,8200,8200,320
     0],
     [2040,2390,2222,2708,2475,8200,2067,2217,2390,8200,8200,2040,2050,215
     0],
     [1940,2485,2047,2608,2253,8200,2042,2360,2485,8200,8200,1940,1950,230
     0]
];

     TransRouteCap = 
     [50000,50000,50000,50000,22500,0,10500,50000,50000,0,0,12000,12000,40
     000];

     TransRouteCost = 
     [900,900,900,900,900,900,900,900,900,900,900,900,900,900];

TransRouteDestinationsCost = [
[900,9999,9999,9999,9999,9999],
[9999,900,9999,9999,9999,9999],
[9999,9999,900,9999,9999,9999],
[9999,9999,9999,900,9999,9999],
[9999,9999,9999,900,9999,9999],
[9999,9999,9999,900,9999,9999],
[9999,9999,9999,900,9999,9999],
[9999,9999,9999,9999,900,9999],
[9999,9999,9999,9999,9999,900],
[9999,9999,9999,9999,900,9999],
[9999,9999,9999,9999,9999,900],
[9999,9999,9999,9999,900,9999],
```

```
[9999,9999,9999,9999,9999,900],
[9999,9999,9999,9999,9999,900]
];

Demand = [
[6806,5410,5235],
[8848,7033,6806],
[7487,5951,5759],
[23821,18935,18324],
[6125,4869,4712],
[15654,12443,12041]
];
```

OPL SCRIPT FOR GHG EMISSIONS MINIMISATION MODEL FORMULATION AND PROBLEM SOLVING USING C-PLEX OPL STUDIO 12.3

```
/*********************************************
* OPL 12.4 Model
* Author: 14406058
* Creation Date: 06/09/2012 at 1:47:31 PM
*********************************************/
 /* CO2 model */

{string} Products = ...;
{string} FarmSize = ...;
{string} T1 = ...;
{string} TradGroup = ...;
int NFactories = ...;
range Factories = 1..NFactories;
{string} EndProducts = ...;

{string} DistNode = ...;
{string} Destinations = ...;
{string} Provinces = ...;
{string} TransRoute = ...;

float Distance[Provinces][Provinces] = ...;

float Production[FarmSize][Provinces] = ...;
float FarmerProdCO2[FarmSize][Products] = ...;
float TransCO2FarmSize[FarmSize][T1][TradGroup] = ... ;

float TradGroupCap[TradGroup][Products][Provinces] = ...;
float TradGroupCO2[TradGroup][Products]= ... ;
float TransCO2TradGroup[Provinces][TradGroup][Factories] = ... ;

float FactCap[Factories][EndProducts] = ...;
float FactProdCO2[Factories][EndProducts]= ... ;
float TransCO2FactDistNode[Factories][DistNode] = ... ;

float DisNodeCap[DistNode] = ...;
float TransDistNodeTransRouteCO2[DistNode][TransRoute]= ... ;
float TransRouteCap[TransRoute] = ...;
float TransRouteCO2[TransRoute] = ...;
     float TransRouteDestinationsCO2[TransRoute][Destinations] = ... ;

float Demand[Destinations][EndProducts] = ...;

dvar float+ X[Provinces,FarmSize,Products,T1,TradGroup];
     dvar float+ Y[Provinces,TradGroup,Factories,EndProducts,DistNode];
dvar float+ Z[EndProducts,DistNode,TransRoute,Destinations];

dexpr float Objective =
      sum(i in Provinces,s in FarmSize,p in Products,t in T1,g in
     TradGroup)(X[i,s,p,t,g]*(FarmerProdCO2[s,p]+TransCO2FarmSize[s,t,g]+T
     radGroupCO2[g,p])) + sum(i in Provinces,g in TradGroup,f in
     Factories,e in EndProducts,a in
     DistNode)(Y[i,g,f,e,a]*(TransCO2TradGroup[i,g,f]+FactProdCO2[f,e]+Tra
     nsCO2FactDistNode[f,a])) + sum(e in EndProducts,a in DistNode, b in
     TransRoute,d in Destinations)
     (Z[e,a,b,d]*(TransDistNodeTransRouteCO2[a,b]+TransRouteCO2[b]+TransRo
     uteDestinationsCO2[b,d]));
```

```
constraint CT1[Provinces][FarmSize];
constraint CT2[Provinces][TradGroup][Products];
constraint CT3[Factories][EndProducts];
constraint CT4[DistNode];
constraint CT5[TransRoute];
constraint CT6[Destinations][EndProducts];
constraint CT7[Provinces][TradGroup];
constraint CT8[EndProducts][DistNode];

minimize Objective;

subject to {

 forall(i in Provinces, s in FarmSize) {
        CT1[i][s]:sum( p in Products,t in T1,g in TradGroup)
    X[i,s,p,t,g] <= Production[s,i];
 }

  forall(i in Provinces, g in TradGroup, p in Products) {
        CT2[i][g][p] :sum(s in FarmSize,t in T1) X[i,s,p,t,g] <=
    TradGroupCap[g,p,i];
 }

  forall(f in Factories,e in EndProducts) {
        CT3[f][e] : sum(i in Provinces,g in TradGroup,a in DistNode)
    Y[i,g,f,e,a] <= FactCap[f,e];
 }

  forall(a in DistNode) {
        CT4[a] : sum(i in Provinces,g in TradGroup,f in Factories,e in
    EndProducts) Y[i,g,f,e,a] <= DisNodeCap[a];
 }

  forall(b in TransRoute) {
        CT5[b] : sum(e in EndProducts,a in DistNode, d in Destinations)
    Z[e,a,b,d] <= TransRouteCap[b];
 }

 forall(d in Destinations,e in EndProducts) {
        CT6[d][e] : sum(a in DistNode, b in TransRoute) Z[e,a,b,d]
    >=Demand[d,e];
 }

 forall (i in Provinces,g in TradGroup){
        CT7[i][g] : sum(s in FarmSize,p in Products,t in T1) X[i,s,p,t,g]
    == sum(f in Factories,e in EndProducts,a in DistNode)Y[i,g,f,e,a];
 }

 forall (e in EndProducts, a in DistNode){
        CT8[e][a] : sum(i in Provinces,g in TradGroup,f in
    Factories)Y[i,g,f,e,a] == sum(b in TransRoute,d in
    Destinations)Z[e,a,b,d];
 }

     ((sum(i in Provinces,g in TradGroup,f in Factories,a in DistNode)
    Y[i,g,f,"STR",a])*0.2+(sum(i in Provinces,g in TradGroup,f in
    Factories,a in DistNode) Y[i,g,f,"RSS",a])) == (sum(i in Provinces,s
    in FarmSize, t in T1,g in TradGroup) X[i,s,"US",t,g]);
```

```
      ((sum(i in Provinces,g in TradGroup,f in Factories,a in DistNode)
     Y[i,g,f,"STR",a])*0.8) == (sum(i in Provinces,s in FarmSize, t in
     T1,g in TradGroup) X[i,s,"CL",t,g]);
      ((sum(i in Provinces,g in TradGroup,f in Factories,a in DistNode)
     Y[i,g,f,"LCT",a])) == (sum(i in Provinces,s in FarmSize, t in T1,g in
     TradGroup) X[i,s,"LX",t,g]);

}
execute
{
 for (i in Provinces){
   for (s in FarmSize){
 writeln(CT1[i][s].dual);
}
}
}
execute
{
 for (i in Provinces){
   for (g in TradGroup){
     for (p in Products){
 writeln(CT2[i][g][p].dual);
}
}
}
}
execute
{
 for (f in Factories){
   for (e in EndProducts){
 writeln(CT3[f][e].dual);
}
}
}
execute
{
 for (a in DistNode){
     writeln(CT4[a].dual);
}
}
execute
{
 for (b in TransRoute){
     writeln(CT5[b].dual);
}
}
execute
{
 for (d in Destinations){
   for (e in EndProducts){
 writeln(CT6[d][e].dual);
}
}
}
execute
{
 for (i in Provinces){
   for (g in TradGroup){
 writeln(CT7[i][g].dual);
}
}
```

```
}
execute
{
 for (e in EndProducts){
   for (a in DistNode){
 writeln(CT8[e][a].dual);
}
}
}

/*********************************************
     * OPL 12.4 Data
* Author: 14406058
     * Creation Date: 06/09/2012 at 1:47:31 PM
     *********************************************/
     /* CO2 model */


     Provinces = { Trang, Pattalung, Satun, Songkhla, Pattani, Yala,
            Narathiwat,Chumporn, Ranong, Surathani, Phangnga, Nakhon,
     Krabi, Phuket};
Products = { US, CL, LX };
FarmSize = { S, M, L };
T1 = { "4W", "10W" };
TradGroup = { DL, GM, CO };
NFactories = 14;
EndProducts = { STR, RSS, LCT };
DistNode = { D1, D2, D3 };

TransRoute = {R1,R2,R3,R4,R5,R6,R7,R8,R9,R10,R11,R12,R13,R14};

Destinations = {CTS, DOS, SKP, PNG, BKK, LCB};

Distance = [
[45,54,116,117,199,217,275,331,289,179,155,106,95,137],
[54,45,111,75,154,178,233,336,306,189,195,92,138,188],
[116,111,45,88,137,135,195,443,404,292,266,202,205,232],
[117,75,88,45,82,105,160,401,378,259,268,154,209,254],
[199,154,137,82,45,38,233,464,449,330,349,224,291,336],
[217,178,135,105,38,45,61,498,480,360,371,255,311,351],
[275,233,195,160,80,61,45,539,528,408,428,303,369,411],
[331,336,443,401,464,498,539,45,83,153,237,246,272,303],
[289,306,404,378,449,480,528,83,45,119,167,225,214,233],
[179,189,292,259,330,360,408,153,119,45,113,105,126,171],
[155,195,266,268,349,371,428,237,167,113,45,158,61,67],
[106,92,202,154,224,255,303,246,225,105,158,45,123,183],
[95,138,205,209,291,311,369,272,214,126,61,123,45,60],
[137,188,232,254,336,351,411,303,233,171,67,183,60,45]
];

Production = [
     [28144, 12109, 6602, 31304, 6375, 22492, 20777,11484, 4325, 39782,
     16594, 31005, 13080, 1831],
     [1513, 651, 355, 1683, 343, 1209, 1117,617, 233, 2139, 892, 1667,
     703, 98],
     [605, 260, 142, 673, 137, 484, 447,247, 93, 856, 357, 667, 281, 39]
];

FarmerProdCO2 = [
[0,0,0],
[0,0,0],
```

```
[0,0,0]
];

TransCO2FarmSize =[
[[0.044,0.088,0.029],
[0.038,0.075,0.025]],
[[0.044,0.088,0.029],
[0.038,0.076,0.025]],
[[0.044,0.029,0.088],
[0.038,0.076,0.025]]
];

TradGroupCap = [
[

     [10705,5174,1070,17930,2230,6601,5602,8653,5977,15076,3211,12043,4282
     ,1427],
     [16057,7761,1606,26896,3345,9902,8430,12979,8965,22614,4817,18064,642
     3,2141],
     [2141,1035,214,3586,446,1320,1124,1731,1195,3015,642,2409,856,285]
],
[
[0,0,0,3616,0,0,0,0,0,3000,0,3300,0,0],
[0,0,0,0,0,0,0,0,0,0,0,0,0,0],
[0,0,0,1004,0,0,0,0,0,1000,0,1000,0,0]
],
[
[0,0,0,0,0,0,0,0,0,0,0,0,0,0],
[0,0,0,0,0,0,0,0,0,0,0,0,0,0],
     [3000,3938, 1313,5063,188,844,281,1031,281,3094,1313,7125,2438,94]
]
];

TradGroupCO2 =[
[0,0,0],
[0,0,0],
[0,0,0]
];

TransCO2TradGroup = [
[
     [0.002,0.002,0.005,0.005,0.009,0.010,0.012,0.015,0.013,0.008,0.007,0.
     005,0.004,0.006],
     [0.002,0.002,0.005,0.005,0.009,0.010,0.012,0.015,0.013,0.008,0.007,0.
     005,0.004,0.006],
     [0.002,0.002,0.005,0.005,0.009,0.010,0.012,0.015,0.013,0.008,0.007,0.
     005,0.004,0.006]
],
[
     [0.002,0.002,0.005,0.003,0.007,0.008,0.010,0.015,0.014,0.009,0.009,0.
     004,0.006,0.008],
     [0.002,0.002,0.005,0.003,0.007,0.008,0.010,0.015,0.014,0.009,0.009,0.
     004,0.006,0.008],
     [0.002,0.002,0.005,0.003,0.007,0.008,0.010,0.015,0.014,0.009,0.009,0.
     004,0.006,0.008]
],
[
     [0.005,0.005,0.002,0.004,0.006,0.006,0.009,0.020,0.018,0.013,0.012,0.
     009,0.009,0.010],
     [0.005,0.005,0.002,0.004,0.006,0.006,0.009,0.020,0.018,0.013,0.012,0.
     009,0.009,0.010],
```

[0.005,0.005,0.002,0.004,0.006,0.006,0.009,0.020,0.018,0.013,0.012,0.
009,0.009,0.010]
],
[
[0.005,0.003,0.004,0.002,0.004,0.005,0.007,0.018,0.017,0.012,0.012,0.
007,0.009,0.011],
[0.005,0.003,0.004,0.002,0.004,0.005,0.007,0.018,0.017,0.012,0.012,0.
007,0.009,0.011],
[0.005,0.003,0.004,0.002,0.004,0.005,0.007,0.018,0.017,0.012,0.012,0.
007,0.009,0.011]
],
[
[0.009,0.007,0.006,0.004,0.002,0.002,0.010,0.021,0.020,0.015,0.016,0.
010,0.013,0.015],
[0.009,0.007,0.006,0.004,0.002,0.002,0.010,0.021,0.020,0.015,0.016,0.
010,0.013,0.015],
[0.009,0.007,0.006,0.004,0.002,0.002,0.010,0.021,0.020,0.015,0.016,0.
010,0.013,0.015]
],
[
[0.010,0.008,0.006,0.005,0.002,0.002,0.003,0.022,0.022,0.016,0.017,0.
011,0.014,0.016],
[0.010,0.008,0.006,0.005,0.002,0.002,0.003,0.022,0.022,0.016,0.017,0.
011,0.014,0.016],
[0.010,0.008,0.006,0.005,0.002,0.002,0.003,0.022,0.022,0.016,0.017,0.
011,0.014,0.016]
],
[
[0.012,0.010,0.009,0.007,0.004,0.003,0.002,0.024,0.024,0.018,0.019,0.
014,0.017,0.018],
[0.012,0.010,0.009,0.007,0.004,0.003,0.002,0.024,0.024,0.018,0.019,0.
014,0.017,0.018],
[0.012,0.010,0.009,0.007,0.004,0.003,0.002,0.024,0.024,0.018,0.019,0.
014,0.017,0.018]
],
[
[0.015,0.015,0.020,0.018,0.021,0.022,0.024,0.002,0.004,0.007,0.011,0.
011,0.012,0.014],
[0.015,0.015,0.020,0.018,0.021,0.022,0.024,0.002,0.004,0.007,0.011,0.
011,0.012,0.014],
[0.015,0.015,0.020,0.018,0.021,0.022,0.024,0.002,0.004,0.007,0.011,0.
011,0.012,0.014]
],
[
[0.013,0.014,0.018,0.017,0.020,0.022,0.024,0.004,0.002,0.005,0.008,0.
010,0.010,0.010],
[0.013,0.014,0.018,0.017,0.020,0.022,0.024,0.004,0.002,0.005,0.008,0.
010,0.010,0.010],
[0.013,0.014,0.018,0.017,0.020,0.022,0.024,0.004,0.002,0.005,0.008,0.
010,0.010,0.010]
],
[
[0.008,0.009,0.013,0.012,0.015,0.016,0.018,0.007,0.005,0.002,0.005,0.
005,0.006,0.008],
[0.008,0.009,0.013,0.012,0.015,0.016,0.018,0.007,0.005,0.002,0.005,0.
005,0.006,0.008],
[0.008,0.009,0.013,0.012,0.015,0.016,0.018,0.007,0.005,0.002,0.005,0.
005,0.006,0.008]
],
[

```
    [0.007,0.009,0.012,0.012,0.016,0.017,0.019,0.011,0.008,0.005,0.002,0.
    007,0.003,0.003],
    [0.007,0.009,0.012,0.012,0.016,0.017,0.019,0.011,0.008,0.005,0.002,0.
    007,0.003,0.003],
    [0.007,0.009,0.012,0.012,0.016,0.017,0.019,0.011,0.008,0.005,0.002,0.
    007,0.003,0.003]
],
[
    [0.005,0.004,0.009,0.007,0.010,0.011,0.014,0.011,0.010,0.005,0.007,0.
    002,0.006,0.008],
    [0.005,0.004,0.009,0.007,0.010,0.011,0.014,0.011,0.010,0.005,0.007,0.
    002,0.006,0.008],
    [0.005,0.004,0.009,0.007,0.010,0.011,0.014,0.011,0.010,0.005,0.007,0.
    002,0.006,0.008]
],
[
    [0.004,0.006,0.009,0.009,0.013,0.014,0.017,0.012,0.010,0.006,0.003,0.
    006,0.002,0.003],
    [0.004,0.006,0.009,0.009,0.013,0.014,0.017,0.012,0.010,0.006,0.003,0.
    006,0.002,0.003],
    [0.004,0.006,0.009,0.009,0.013,0.014,0.017,0.012,0.010,0.006,0.003,0.
    006,0.002,0.003]
],
[
    [0.006,0.008,0.010,0.011,0.015,0.016,0.018,0.014,0.010,0.008,0.003,0.
    008,0.003,0.002],
    [0.006,0.008,0.010,0.011,0.015,0.016,0.018,0.014,0.010,0.008,0.003,0.
    008,0.003,0.002],
    [0.006,0.008,0.010,0.011,0.015,0.016,0.018,0.014,0.010,0.008,0.003,0.
    008,0.003,0.002]
]
];

FactCap = [
[16783,16783,50348],
[0,0,0],
[0,0,0],
[43700,50983,50983],
[0,0,0],
[0,0,0],
[0,0,0],
[0,0,0],
[0,0,0],
[80764,40382,40382],
[0,0,0],
[32416,10805,10805],
[0,0,0],
[0,0,0]
];


FactProdCO2 = [
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
```

```
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54],
[0.70,0.64,0.54]
];

TransCO2FactDistNode = [
[0.154,0.235,0.139 ],
[0.098,0.248,0.121 ],
[0.116,0.383,0.265 ],
[0.059,0.340,0.202 ],
[0.108,0.433,0.294 ],
[0.138,0.473,0.335 ],
[0.210,0.536,0.398 ],
[0.526,0.201,0.323 ],
[0.496,0.156,0.295 ],
[0.340,0.079,0.138 ],
[0.352,0.148,0.207 ],
[0.202,0.138,0.079 ],
[0.274,0.165,0.161 ],
[0.333,0.224,0.240 ]
];

DisNodeCap = [500000,500000,500000];

     TransRouteCap =
     [50000,50000,50000,50000,22500,0,10500,50000,50000,0,0,12000,12000,40
     000];

     TransRouteCO2 =
     [0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.01,0.0
     1];

TransRouteDestinationsCO2 = [
[0.01,100,100,100,100,100],
[100,0.01,100,100,100,100],
[100,100,0.01,100,100,100],
[100,100,100,0.01,100,100],
[100,100,100,0.01,100,100],
[100,100,100,0.01,100,100],
[100,100,100,0.01,100,100],
[100,100,100,100,0.01,100],
[100,100,100,100,100,0.01],
[100,100,100,100,0.01,100],
[100,100,100,100,100,0.01],
[100,100,100,100,0.01,100],
[100,100,100,100,100,0.01],
[100,100,100,100,100,0.01]
];

Demand = [
[6806,5410,5235],
[8848,7033,6806],
[7487,5951,5759],
[23821,18935,18324],
[6125,4869,4712],
[15654,12443,12041]
];
```

SETS, PARAMETERS AND VARIABLE DESCRIPTIONS

$i \in I$	Set of provinces (i = Trang, Pattalung, Satun, Songkhla, Pattani, Yala, Narathiwat, Chumporn, Ranong, Suratthani, Phangnga, Nakhon Si Thammarat, Krabi, Phuket)
$p \in P$	Set of primary rubber products (p = US, CL, LX) US = unsmoked- sheet, CL = cup- lump, LX = latex concentrate
$s \in S$	Set of rubber farmer sizes (s = S, M, L) S = small, M= medium, L= large
$t \in T$	Set of truck types (t = 4W, 10W) 4W = 4 wheels-truck, 10W = 10 wheels-truck
$g \in G$	Set of trader groups (g = DL, GM, CO) DL = dealer, GM = general market, CO = cooperative
$f \in F$	Set of factories (f = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14) 1= summation of all factories capacity in Trang province 2= summation of all factories capacity in Pattalung province 3= summation of all factories capacity in Satun province

4= summation of all factories capacity in Songkhla province

5= summation of all factories capacity in Pattani province

6= summation of all factories capacity in Yala province

7= summation of all factories capacity in Narathiwat province

8= summation of all factories capacity in Chumporn province

9= summation of all factories capacity in Ranong province

10= summation of all factories capacity in Suratthani province

11= summation of all factories capacity in Phangnga province

12= summation of all factories capacity in Nakhon Si Thammarat

13= summation of all factories capacity in Krabi province

14= summation of all factories capacity in Phuket province

$e \in E$ Set of intermediate rubber products

(e = STR, RSS, LCT)

STR= block rubber, RSS = ripped-smoked sheet, LCT=latex concentrate

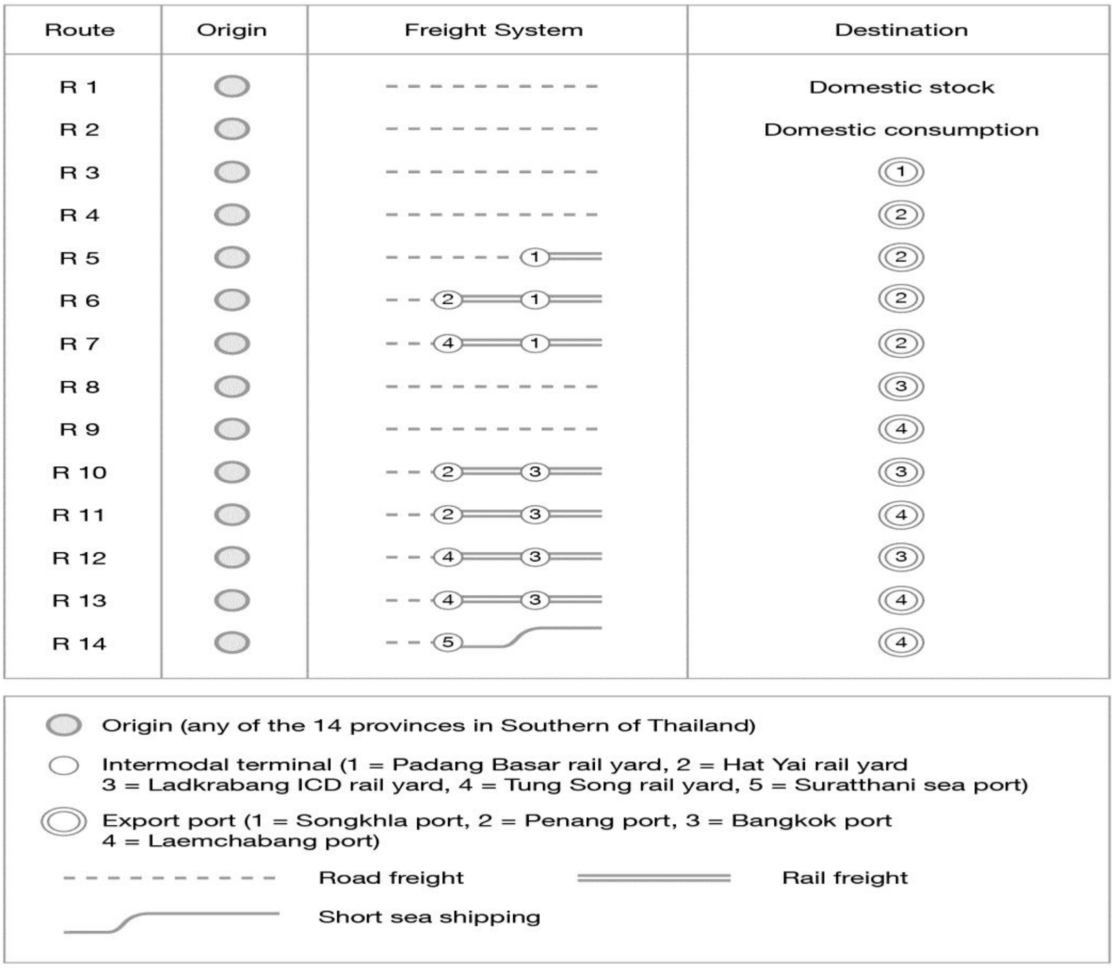
$a \in A$ Set of gateway nodes

(a = D1, D2, D3)

D1= Songkhla province , D2=Suratthani province, D3= Nakhon Si Thammarat province

$b \in B$ Set of intermodal freight routes

(b = R1, R2,R3, R4, R5,R6,R7,R8,R9,R10,R11,R12,R13,R14)



$d \epsilon D$ Set of domestic destination and exporting port

(d = CTS, DOS, SKP, PNG, BKK, LCB)

CTS = domestic stock,

DOS = domestic consumption,

SKP = Songkhla port,

PNG = Penang port ,

BKK = Bangkok port,

LCB = Laemchabang port

VARIABLE AND PARAMETER VALUES

Table A-1: Rubber cultivation capacity: SC_{si} (Unit: Ton/Month)

Source: The Rubber Thai Association Statistic 2010 (TRA 2010)

SC_{si}		s		
		S	M	L
i	Trang	28,144	1,513	605
	Pattalung	12,109	651	260
	Satun	6,602	355	142
	Songkhla	31,301	1,683	673
	Pattani	6,375	343	137
	Yala	22,492	1,209	484
	Narathiwat	20,777	1,117	447
	Chumporn	11,484	617	247
	Ranong	4,325	233	93
	Suratthani	39,782	2,139	856
	Phangnga	16,594	892	357
	Nakhon Si Thammarat	31,005	1,667	667
	Krabi	13,080	703	281
	Phuket	1,831	98	39

Table A-2: Trader group capacity: TG_{gpi} (Unit: Ton/Month)

Source: The Rubber Thai Association Statistic 2010 (TRA 2010)

TG_{gpi}	DL			GM			CO		
	US	CL	LX	US	CL	LX	US	CL	LX
Trang	10,705	16,057	2,141	0	0	0	0	0	3,000
Pattalung	5,174	7,761	1,035	0	0	0	0	0	3,938
Satun	1,070	1,606	214	0	0	0	0	0	1,313
Songkhla	17,930	26,896	3,586	3,616	0	1,004	0	0	5,063
Pattani	2,230	3,345	446	0	0	0	0	0	188
Yala	6,601	9,902	1,320	0	0	0	0	0	844
Narathiwat	5,620	8,430	1,124	0	0	0	0	0	281
Chumporn	8,653	12,979	1,731	0	0	0	0	0	1,031
Ranong	5,977	8,965	1,195	0	0	0	0	0	281
Suratthani	15,076	22,614	3,015	3,000	0	1,000	0	0	3,094
Phangnga	3,211	4,817	642	0	0	0	0	0	1,313
Nakhon Si Thammarat	12,043	18,064	2,409	3,300	0	1,000	0	0	7,125
Krabi	4,282	6,423	856	0	0	0	0	0	2,438
Phuket	1,427	2,141	285	0	0	0	0	0	94

Table A-3: Factory production capacity: FC_{fe} (unit : Ton/Month)

Source: The Rubber Thai Association Statistic 2010 (TRA 2010)

FC_{fe}		e		
		STR	RSS	LCT
f	Trang (1)	16,783	16,783	50,348
	Pattalung (2)	0	0	0
	Satun (3)	0	0	0
	Songkhla (4)	43,700	50,983	50,983
	Pattani (5)	0	0	0
	Yala (6)	0	0	0
	Narathiwat (7)	0	0	0
	Chumporn (8)	0	0	0
	Ranong (9)	0	0	0
	Suratthani (10)	80,764	40,382	40,382
	Phangnga (11)	0	0	0
	Nakhon Si Thammarat (12)	32,416	10,805	10,805
	Krabi (13)	0	0	0
	Phuket (14)	0	0	0

Table A-4: Gateway node capacity: DNC_a (unit: Ton)

The gateway node capacity is assumed to be 500,000 Ton for the balancing flow purpose. In the current practice, the gateway node has no capacity limited.

DNC_a	D1	D2	D3
	500,000	500,000	500,000

Table A-5: Freight route capacity: FRC_b (unit: Ton/Month)

Source: The state railway of Thailand 2010 (State Railway of Thailand 2011)

FRC_b	
R1	50,000
R2	50,000
R3	50,000
R4	50,000
R5	22,500
R6	0
R7	10,500
R8	50,000
R9	50,000
R10	0
R11	0
R12	12,000
R13	12,000
R14	40,000

Table A-6: Demand: DE_{de} (unit : Ton/Month)

Source: The Rubber Thai Association Statistic 2010 (TRA 2010)

DE_{de}		e		
		STR	RSS	LCT
d	CTS	6,806	5,410	5,235
	DOS	8,848	7,033	6,806
	SKP	7,487	5,951	5,759
	PNG	23,821	18,935	18,324
	BKK	6,125	4,869	4,712
	LCB	15,654	12,443	12,041

COST PARAMETERS

Table A-7: Cost of farmer to process primary rubber products: CR_{sp} (Unit: Baht)

Source: Office of Agricultural Economics, Ministry of Agricultural and Cooperative (OAE 2011)

CR_{sp}		p		
		US	CL	LX
s	S	81,480	69,260	68,400
	M	77,406	65,797	65,018
	L	69,258	55,927	58,174

Table A-8: Cost of transport primary rubber products from farmer to trader group by each truck type: CT_{stg} (Unit: Baht/Ton)

Source: Starlight express shipping (Starlight Shipping 2012)

CT_{stg}		g		
s	t	DL	GM	CO
S	4 wheels	600	560	580
	10 wheels	650	650	650
M	4 wheels	600	560	580
	10 wheels	600	560	580
L	4 wheels	560	600	580
	10 wheels	520	550	540

Table A-9: Cost of trading primary rubber products in each trader group: CG_{gp} (Unit: Baht/Ton)

Source: Sri Trang Agro Industry Public company (STA 2012a)

CG_{gp}		p		
		US	CL	LX
g	DL	600	600	600
	GM	580	580	580
	CO	560	560	560

Table A-10: Cost of transport primary rubber products from trader group in each province to each factory: CT_{igf} (Unit: Baht)

Costs of transport intermediate rubber products from each factory to gateway node = cost per ton-km $\times$ travelled distance from each factory to each distribution node.

(See table B-16 for distance table (cost per ton-km for GM is 66 Baht per ton, CO is 64 Baht per ton, DL is 68 Baht/ton))

GM	**Trang**	**Pattalung**	**Satun**	**Songkhla**	**Pattani**	**Yala**	**Narathiwat**	**Chumporn**	**Ranong**	**Surat thani**	**Phangnga**	**Nakhon Si Thammarat**	**Krabi**	**Phuket**
Trang	2,970	3,564	7,656	7,722	13,134	14,322	18,150	21,846	19,074	11,814	10,230	6,996	6,270	9,042
Pattalung	3,564	2,970	7,326	4,950	10,164	11,748	15,378	22,176	20,196	12,474	12,870	6,072	9,108	12,408
Satun	7,656	7,326	2,970	5,808	9,042	8,910	12,870	29,238	26,664	19,272	17,556	13,332	13,530	15,312
Songkhla	7,722	4,950	5,808	2,970	5,412	6,930	10,560	26,466	24,948	17,094	17,688	10,164	13,794	16,764
Pattani	13,134	10,164	9,042	5,412	2,970	2,508	15,378	30,624	29,634	21,780	23,034	14,784	19,206	22,176
Yala	14,322	11,748	8,910	6,930	2,508	2,970	4,026	32,868	31,680	23,760	24,486	16,830	20,526	23,166
Narathiwat	18,150	15,378	12,870	10,560	5,280	4,026	2,970	35,574	34,848	26,928	28,248	19,998	24,354	27,126
Chumporn	21,846	22,176	29,238	26,466	30,624	32,868	35,574	2,970	5,478	10,098	15,642	16,236	17,952	19,998
Ranong	19,074	20,196	26,664	24,948	29,634	31,680	34,848	5,478	2,970	7,854	11,022	14,850	14,124	15,378
Suratthani	11,814	12,474	19,272	17,094	21,780	23,760	26,928	10,098	7,854	2,970	7,458	6,930	8,316	11,286
Phangnga	10,230	12,870	17,556	17,688	23,034	24,486	28,248	15,642	11,022	7,458	2,970	10,428	4,026	4,422
Nakhon	6,996	6,072	13,332	10,164	14,784	16,830	19,998	16,236	14,850	6,930	10,428	2,970	8,118	12,078
Krabi	6,270	9,108	13,530	13,794	19,206	20,526	24,354	17,952	14,124	8,316	4,026	8,118	2,970	3,960
Phuket	9,042	12,408	15,312	16,764	22,176	23,166	27,126	19,998	15,378	11,286	4,422	12,078	3,960	2,970
CO	**Trang**	**Pattalung**	**Satun**	**Songkhla**	**Pattani**	**Yala**	**Narathiwat**	**Chumporn**	**Ranong**	**Surat thani**	**Phangnga**	**Nakhon Si Thammat**	**Krabi**	**Phuket**
Trang	2,880	3,456	7,424	7,488	12,736	13,888	17,600	21,184	18,496	11,456	9,920	6,784	6,080	8,768
Pattalung	3,456	2,880	7,104	4,800	9,856	11,392	14,912	21,504	19,584	12,096	12,480	5,888	8,832	12,032
Satun	7,424	7,104	2,880	5,632	8,768	8,640	12,480	28,352	25,856	18,688	17,024	12,928	13,120	14,848
Songkhla	7,488	4,800	5,632	2,880	5,248	6,720	10,240	25,664	24,192	16,576	17,152	9,856	13,376	16,256
Pattani	12,736	9,856	8,768	5,248	2,880	2,432	14,912	29,696	28,736	21,120	22,336	14,336	18,624	21,504
Yala	13,888	11,392	8,640	6,720	2,432	2,880	3,904	31,872	30,720	23,040	23,744	16,320	19,904	22,464
Narathiwat	17,600	14,912	12,480	10,240	5,120	3,904	2,880	34,496	33,792	26,112	27,392	19,392	23,616	26,304
Chumporn	21,184	21,504	28,352	25,664	29,696	31,872	34,496	2,880	5,312	9,792	15,168	15,744	17,408	19,392
Ranong	18,496	19,584	25,856	24,192	28,736	30,720	33,792	5,312	2,880	7,616	10,688	14,400	13,696	14,912
Suratthani	11,456	12,096	18,688	16,576	21,120	23,040	26,112	9,792	7,616	2,880	7,232	6,720	8,064	10,944

Table A-10: Cost of transport primary rubber products from trader group in each province to each factory: CT_{igf} (Unit: Baht) – continued from previous page

CO	Trang	Pattalung	Satun	Songkhla	Pattani	Yala	Narathiwat	Chumporn	Ranong	Surat thani	Phangnga	Nakhon Si Thammat	Krabi	Phuket
Phangnga	9,920	12,480	17,024	17,152	22,336	23,744	27,392	15,168	10,688	7,232	2,880	10,112	3,904	4,288
Nakhon	6,784	5,888	12,928	9,856	14,336	16,320	19,392	15,744	14,400	6,720	10,112	2,880	7,872	11,712
Krabi	6,080	8,832	13,120	13,376	18,624	19,904	23,616	17,408	13,696	8,064	3,904	7,872	2,880	3,840
Phuket	8,768	12,032	14,848	16,256	21,504	22,464	26,304	19,392	14,912	10,944	4,288	11,712	3,840	2,880
DL	**Trang**	**Pattalung**	**Satun**	**Songkhla**	**Pattani**	**Yala**	**Narathiwat**	**Chumporn**	**Ranong**	**Surat thani**	**Phangnga**	**Nakhon Si Thammarat**	**Krabi**	**Phuket**
Trang	3,060	3,672	7,888	7,956	13,532	14,756	18,700	22,508	19,652	12,172	10,540	7,208	6,460	9,316
Pattalung	3,672	3,060	7,548	5,100	10,472	12,104	15,844	22,848	20,808	12,852	13,260	6,256	9,384	12,784
Satun	7,888	7,548	3,060	5,984	9,316	9,180	13,260	30,124	27,472	19,856	18,088	13,736	13,940	15,776
Songkhla	7,956	5,100	5,984	3,060	5,576	7,140	10,880	27,268	25,704	17,612	18,224	10,472	14,212	17,272
Pattani	13,532	10,472	9,316	5,576	3,060	2,584	15,844	31,552	30,532	22,440	23,732	15,232	19,788	22,848
Yala	14,756	12,104	9,180	7,140	2,584	3,060	4,148	33,864	32,640	24,480	25,228	17,340	21,148	23,868
Narathiwat	18,700	15,844	13,260	10,880	5,440	4,148	3,060	36,652	35,904	27,744	29,104	20,604	25,092	27,948
Chumporn	22,508	22,848	30,124	27,268	31,552	33,864	36,652	3,060	5,644	10,404	16,116	16,728	18,496	20,604
Ranong	19,652	20,808	27,472	25,704	30,532	32,640	35,904	5,644	3,060	8,092	11,356	15,300	14,552	15,844
Suratthani	12,172	12,852	19,856	17,612	22,440	24,480	27,744	10,404	8,092	3,060	7,684	7,140	8,568	11,628
Phangnga	10,540	13,260	18,088	18,224	23,732	25,228	29,104	16,116	11,356	7,684	3,060	10,744	4,148	4,556
Nakhon	7,208	6,256	13,736	10,472	15,232	17,340	20,604	16,728	15,300	7,140	10,744	3,060	8,364	12,444
Krabi	6,460	9,384	13,940	14,212	19,788	21,148	25,092	18,496	14,552	8,568	4,148	8,364	3,060	4,080
Phuket	9,316	12,784	15,776	17,272	22,848	23,868	27,948	20,604	15,844	11,628	4,556	12,444	4,080	3,060

Table A-11: Cost of factory to process intermediate rubber products: CF_{fe} (Unit : Baht/Ton) (Kunarasiri and Srivarin 2007)

CF_{fe}		e		
		RSS	STR	LCT
f	Trang (1)	3,000	3,410	2,800
	Pattalung (2)	3,000	3,410	2,800
	Satun (3)	3,000	3,410	2,800
	Songkhla (4)	3,000	3,410	2,800
	Pattani (5)	3,000	3,410	2,800
	Yala (6)	3,000	3,410	2,800
	Narathiwat (7)	3,000	3,410	2,800
	Chumporn (8)	3,000	3,410	2,800
	Ranong (9)	3,000	3,410	2,800
	Suratthani (10)	3,000	3,410	2,800
	Phangnga (11)	3,000	3,410	2,800
	Nakhon Si Thammarat (12)	3,000	3,410	2,800
	Krabi (13)	3,000	3,410	2,800
	Phuket (14)	3,000	3,410	2,800

Table A-12: Cost of transport intermediate rubber products from each factory to gateway node: CT_{fa} (Unit : Baht)

Costs of transport intermediate rubber products from each factory to gateway node = cost per ton-km (100 baht/Ton-km) × travelled distance from each factory to each distribution node.

See table B-16 for distance table

CT_{fa}		a		
		D1	D2	D3
f	Trang (1)	11,700	17,900	10,600
	Pattalung (2)	7,500	18,900	9,200
	Satun (3)	8,800	29,200	20,200
	Songkhla (4)	4,500	25,900	15,400
	Pattani (5)	8,200	33,000	22,400
	Yala (6)	10,500	36,000	25,500
	Narathiwat (7)	16,000	40,800	30,300
	Chumporn (8)	40,100	15,300	24,600
	Ranong (9)	37,800	11,900	22,500
	Suratthani (10)	25,900	6,000	10,500
	Phangnga (11)	26,800	11,300	15,800
	Nakhon Si Thammarat (12)	15,400	10,500	6,000
	Krabi (13)	20,900	12,600	12,300
	Phuket (14)	25,400	17,100	18,300

Table A-13: Cost of transport intermediate rubber products from gateway node to freight route: CT_{ab} (Unit: Baht/Ton)

Source: Starlight express shipping (Starlight Shipping 2012)

CT_{ab}		a		
		D1	D2	D3
b	R1	2,510	2,040	1,940
	R2	2,560	2,390	2,485
	R3	1,797	2,222	2,047
	R4	2,357	2,708	2,608
	R5	2,128	2,475	2,253
	R6	8,200	8,200	8,200
	R7	8,200	2,067	2,042
	R8	2,510	2,217	2,360
	R9	2,560	2,390	2,485
	R10	8,200	8,200	8,200
	R11	8,200	8,200	8,200
	R12	8,200	2,040	1,940
	R13	8,200	2,050	1,950
	R14	3,200	2,150	2,300

Table A-14: Cost of exporting intermediate rubber products via freight route: CM_b (Unit: Baht/Ton)

Source: Sri Trang Agro Industry Public company (STA 2012a)

CM_b	
R1	900
R2	900
R3	900
R4	900
R5	900
R6	900
R7	900
R8	900
R9	900
R10	900
R11	900
R12	900
R13	900
R14	900

Table A-15: Cost of exporting intermediate rubber products from freight route to destination: CT_{bd} (Unit: Baht/Ton)

Cost at 9,999 was assumed for conservation flow

CT_{bd}		d					
		CTS	DOS	SKP	PNG	BKK	LCB
b	R1	900	9,999	9,999	9,999	9,999	9,999
	R2	9,999	900	9,999	9,999	9,999	9,999
	R3	9,999	9,999	900	9,999	9,999	9,999
	R4	9,999	9,999	9,999	900	9,999	9,999
	R5	9,999	9,999	9,999	900	9,999	9,999
	R6	9,999	9,999	9,999	900	9,999	9,999
	R7	9,999	9,999	9,999	900	9,999	9,999
	R8	9,999	9,999	9,999	9,999	900	9,999
	R9	9,999	9,999	9,999	9,999	9,999	900
	R10	9,999	9,999	9,999	9,999	900	9,999
	R11	9,999	9,999	9,999	9,999	9,999	900
	R12	9,999	9,999	9,999	9,999	900	9,999
	R13	9,999	9,999	9,999	9,999	9,999	900
	R14	9,999	9,999	9,999	9,999	9,999	900

Table A-16: Distance table

Source: http://distancecalculator.globefeed.com/Thailand_Distance_Calculator.asp

Province	Trang	Pattalung	satun	Songkhla	Pattani	Yala	Narathiwat	Chumporn	Ranong	Surat thani	Phangnga	Nakhon	Krabi	Phuket
Trang	1	54	116	117	199	217	275	331	289	179	155	106	95	137
Pattalung	54	1	111	75	154	178	233	336	306	189	195	92	138	188
Satun	116	111	1	88	137	135	195	443	404	292	266	202	205	232
Songkhla	117	75	88	1	82	105	160	401	378	259	268	154	209	254
Pattani	199	154	137	82	1	38	233	464	449	330	349	224	291	336
Yala	217	178	135	105	38	1	61	498	480	360	371	255	311	351
Narathiwat	275	233	195	160	80	61	1	539	528	408	428	303	369	411
Chumporn	331	336	443	401	464	498	539	1	83	153	237	246	272	303
Ranong	289	306	404	378	449	480	528	83	1	119	167	225	214	233
Surat thani	179	189	292	259	330	360	408	153	119	1	113	105	126	171
Phangnga	155	195	266	268	349	371	428	237	167	113	1	158	61	67
Nakhon	106	92	202	154	224	255	303	246	225	105	158	1	123	183
Krabi	95	138	205	209	291	311	369	272	214	126	61	123	1	60
Phuket	137	188	232	254	336	351	411	303	233	171	67	183	60	1

ENVIRONMENTAL PARAMETERS

Table A-17: GHG emissions of farmer to process primary rubber products: ER_{sp} (Unit: Baht/Ton) (Jawjit, Kroeze and Rattanapan 2010)

ER_{sp}		p		
		US	CL	LX
s	S	0	0	0
	M	0	0	0
	L	0	0	0

Table A-18: GHG emissions of transport primary rubber products from farmer to trader group by each truck type: ET_{stg} (Unit : Baht/Ton) (Jawjit, Kroeze and Rattanapan 2010)

ET_{stg}		g		
s	t	DL	GM	CO
S	4 wheels	0.044	0.088	0.029
	10 wheels	0.038	0.076	0.025
M	4 wheels	0.044	0.088	0.029
	10 wheels	0.038	0.076	0.025
L	4 wheels	0.044	0.038	0.029
	10 wheels	0.038	0.076	0.025

Table A-19: GHG emissions of trading primary rubber products in each trader group: EG_{gp} (Unit: Baht/Ton)

This value is assume to be 0

EG_{gp}		p		
		US	CL	LX
g	DL	0	0	0
	GM	0	0	0
	CO	0	0	0

Table A-20: GHG emissions of transport primary rubber products from trader group in each province to each factory: ET_{igf} (Unit : Baht/Ton)

Greenhouse gas emissions (ton) = weight of goods (ton) $\times$ *total distance travelled (kilometre)* $\times$ *GHG conversion factor (ton CO_2 –eq. / ton kilometre)*. (Weight of goods is 25 tons, see table 2-3 for GHG conversion factor and table B-16 for distance between provinces)

GM	Trang	Pattalung	Satun	Songkhla	Pattani	Yala	Narathiwat	Chumporn	Ranong	Suratthani	Phangnga	Nakhon Si Thammarat	Krabi	Phuket
Trang	0.002	0.002	0.005	0.005	0.009	0.010	0.012	0.015	0.013	0.008	0.007	0.005	0.004	0.006
Pattalung	0.002	0.002	0.005	0.003	0.007	0.008	0.010	0.015	0.014	0.009	0.009	0.004	0.006	0.008
Satun	0.005	0.005	0.002	0.004	0.006	0.006	0.009	0.020	0.018	0.013	0.012	0.009	0.009	0.010
Songkhla	0.005	0.003	0.004	0.002	0.004	0.005	0.007	0.018	0.017	0.012	0.012	0.007	0.009	0.011
Pattani	0.009	0.007	0.006	0.004	0.002	0.002	0.010	0.021	0.020	0.015	0.016	0.010	0.013	0.015
Yala	0.010	0.008	0.006	0.005	0.002	0.002	0.003	0.022	0.022	0.016	0.017	0.011	0.014	0.016
Narathiwat	0.012	0.010	0.009	0.007	0.004	0.003	0.002	0.024	0.024	0.018	0.019	0.014	0.017	0.018
Chumporn	0.015	0.015	0.020	0.018	0.021	0.022	0.024	0.002	0.004	0.007	0.011	0.011	0.012	0.014
Ranong	0.013	0.014	0.018	0.017	0.020	0.022	0.024	0.004	0.002	0.005	0.008	0.010	0.010	0.010
Surat thani	0.008	0.009	0.013	0.012	0.015	0.016	0.018	0.007	0.005	0.002	0.005	0.005	0.006	0.008
Phangnga	0.007	0.009	0.012	0.012	0.016	0.017	0.019	0.011	0.008	0.005	0.002	0.007	0.003	0.003
Nakhon	0.005	0.004	0.009	0.007	0.010	0.011	0.014	0.011	0.010	0.005	0.007	0.002	0.006	0.008
Krabi	0.004	0.006	0.009	0.009	0.013	0.014	0.017	0.012	0.010	0.006	0.003	0.006	0.002	0.003
Phuket	0.006	0.008	0.010	0.011	0.015	0.016	0.018	0.014	0.010	0.008	0.003	0.008	0.003	0.002
CO	**Trang**	**Pattalung**	**Satun**	**Songkhla**	**Pattani**	**Yala**	**Narathiwat**	**Chumporn**	**Ranong**	**Suratthani**	**Phangnga**	**Nakhon Si Thmmarat**	**Krabi**	**Phuket**
Trang	0.002	0.002	0.005	0.005	0.009	0.010	0.012	0.015	0.013	0.008	0.007	0.005	0.004	0.006
Pattalung	0.002	0.002	0.005	0.003	0.007	0.008	0.010	0.015	0.014	0.009	0.009	0.004	0.006	0.008
Satun	0.005	0.005	0.002	0.004	0.006	0.006	0.009	0.020	0.018	0.013	0.012	0.009	0.009	0.010
Songkhla	0.005	0.003	0.004	0.002	0.004	0.005	0.007	0.018	0.017	0.012	0.012	0.007	0.009	0.011
Pattani	0.009	0.007	0.006	0.004	0.002	0.002	0.010	0.021	0.020	0.015	0.016	0.010	0.013	0.015
Yala	0.010	0.008	0.006	0.005	0.002	0.002	0.003	0.022	0.022	0.016	0.017	0.011	0.014	0.016
Narathiwat	0.012	0.010	0.009	0.007	0.004	0.003	0.002	0.024	0.024	0.018	0.019	0.014	0.017	0.018
Chumporn	0.015	0.015	0.020	0.018	0.021	0.022	0.024	0.002	0.004	0.007	0.011	0.011	0.012	0.014
Ranong	0.013	0.014	0.018	0.017	0.020	0.022	0.024	0.004	0.002	0.005	0.008	0.010	0.010	0.010
Surat thani	0.008	0.009	0.013	0.012	0.015	0.016	0.018	0.007	0.005	0.002	0.005	0.005	0.006	0.008

Table A-20: GHG emissions of transport primary rubber products from trader group in each province to each factory: ET_{igf} (Unit : Baht/Ton) - Continued from previous page

CO	Trang	Pattalung	Satun	Songkhla	Pattani	Yala	Narathiwat	Chumporn	Ranong	Surat thani	Phangnga	Nakhon Si Thammat	Krabi	Phuket
Phangnga	0.007	0.009	0.012	0.012	0.016	0.017	0.019	0.011	0.008	0.005	0.002	0.007	0.003	0.003
Nakhon	0.005	0.004	0.009	0.007	0.010	0.011	0.014	0.011	0.010	0.005	0.007	0.002	0.006	0.008
Krabi	0.004	0.006	0.009	0.009	0.013	0.014	0.017	0.012	0.010	0.006	0.003	0.006	0.002	0.003
Phuket	0.006	0.008	0.010	0.011	0.015	0.016	0.018	0.014	0.010	0.008	0.003	0.008	0.003	0.002

DL	Trang	Pattalung	Satun	Songkhla	Pattani	Yala	Narathiwat	Chumporn	Ranong	Surat thani	Phangnga	Nakhon Si Thammarat	Krabi	Phuket
Trang	0.002	0.002	0.005	0.005	0.009	0.010	0.012	0.015	0.013	0.008	0.007	0.005	0.004	0.006
Pattalung	0.002	0.002	0.005	0.003	0.007	0.008	0.010	0.015	0.014	0.009	0.009	0.004	0.006	0.008
Satun	0.005	0.005	0.002	0.004	0.006	0.006	0.009	0.020	0.018	0.013	0.012	0.009	0.009	0.010
Songkhla	0.005	0.003	0.004	0.002	0.004	0.005	0.007	0.018	0.017	0.012	0.012	0.007	0.009	0.011
Pattani	0.009	0.007	0.006	0.004	0.002	0.002	0.010	0.021	0.020	0.015	0.016	0.010	0.013	0.015
Yala	0.010	0.008	0.006	0.005	0.002	0.002	0.003	0.022	0.022	0.016	0.017	0.011	0.014	0.016
Narathiwat	0.012	0.010	0.009	0.007	0.004	0.003	0.002	0.024	0.024	0.018	0.019	0.014	0.017	0.018
Chumporn	0.015	0.015	0.020	0.018	0.021	0.022	0.024	0.002	0.004	0.007	0.011	0.011	0.012	0.014
Ranong	0.013	0.014	0.018	0.017	0.020	0.022	0.024	0.004	0.002	0.005	0.008	0.010	0.010	0.010
Suratthani	0.008	0.009	0.013	0.012	0.015	0.016	0.018	0.007	0.005	0.002	0.005	0.005	0.006	0.008
Phangnga	0.007	0.009	0.012	0.012	0.016	0.017	0.019	0.011	0.008	0.005	0.002	0.007	0.003	0.003
Nakhon	0.005	0.004	0.009	0.007	0.010	0.011	0.014	0.011	0.010	0.005	0.007	0.002	0.006	0.008
Krabi	0.004	0.006	0.009	0.009	0.013	0.014	0.017	0.012	0.010	0.006	0.003	0.006	0.002	0.003
Phuket	0.006	0.008	0.010	0.011	0.015	0.016	0.018	0.014	0.010	0.008	0.003	0.008	0.003	0.002

Table A-21: GHG emissions of factory to process intermediate rubber products: EF_{fe} (Unit: Baht/Ton) (Jawjit, Kroeze and Rattanapan 2010)

EF_{fe}		e		
		RSS	STR	LCT
f	Trang (1)	0.64	0.70	0.54
	Pattalung (2)	0.64	0.70	0.54
	Satun (3)	0.64	0.70	0.54
	Songkhla (4)	0.64	0.70	0.54
	Pattani (5)	0.64	0.70	0.54
	Yala (6)	0.64	0.70	0.54
	Narathiwat (7)	0.64	0.70	0.54
	Chumporn (8)	0.64	0.70	0.54
	Ranong (9)	0.64	0.70	0.54
	Suratthani (10)	0.64	0.70	0.54
	Phangnga (11)	0.64	0.70	0.54
	Nakhon Si Thammarat (12)	0.64	0.70	0.54
	Krabi (13)	0.64	0.70	0.54
	Phuket (14)	0.64	0.70	0.54

Table A-22: GHG emissions of transport intermediate rubber products from each factory to gateway node: ET_{fa} (Unit: Baht/Ton)

Greenhouse gas emissions (ton) = weight of goods (ton) × total distance travelled (kilometre) × GHG conversion factor (ton CO_2–eq. / ton kilometre)

(Weight of goods is 25 Tons, see table 2-3 for GHG conversion factor and table B-16 for distance between provinces)

ET_{fa}		a		
		D1	D2	D3
f	Trang (1)	0.154	0.235	0.139
	Pattalung (2)	0.098	0.248	0.121
	Satun (3)	0.116	0.383	0.265
	Songkhla (4)	0.059	0.340	0.202
	Pattani (5)	0.108	0.433	0.294
	Yala (6)	0.138	0.473	0.335
	Narathiwat (7)	0.210	0.536	0.398
	Chumporn (8)	0.526	0.201	0.323
	Ranong (9)	0.496	0.156	0.295
	Suratthani (10)	0.340	0.079	0.138
	Phangnga (11)	0.352	0.148	0.207
	Nakhon Si Thammarat (12)	0.202	0.138	0.079
	Krabi (13)	0.274	0.165	0.161
	Phuket (14)	0.333	0.224	0.240

Table A-23: GHG emissions of transport intermediate rubber products from gateway node to freight route: ET_{ab} (Unit: Baht/Ton)

Greenhouse gas emissions (ton) = weight of goods (ton) × total distance travelled (kilometre) × GHG conversion factor (ton CO_2–eq. / ton kilometre)

(Weight of goods is 25 Tons, see table 2-3 for GHG conversion factor and table B-16 for distance between provinces)

ET_{ab}		a		
		D1	D2	D3
b	R1	0.9555	0.6956	0.7875
	R2	0.8033	0.5880	0.6458
	R3	0.0394	0.5250	0.2021
	R4	0.2363	0.7219	0.2678
	R5	0.1459	0.6446	0.2903
	R6	0.0969	0.5694	0.2741
	R7	0.5603	0.3634	0.2124
	R8	1.5750	0.8531	0.8531
	R9	1.8375	1.1156	0.7219
	R10	0.3439	0.8164	0.5211
	R11	0.3855	0.8580	0.5627
	R12	0.5741	0.3773	0.2263
	R13	0.6154	0.4189	0.2679
	R14	0.9865	0.4615	0.5271

Table A-24: GHG emissions of exporting intermediate rubber products via freight route: EM_b (Unit: Baht/Ton) (Jawjit, Kroeze and Rattanapan 2010)

GM_b	
R1	0.01
R2	0.01
R3	0.01
R4	0.01
R5	0.01
R6	0.01
R7	0.01
R8	0.01
R9	0.01
R10	0.01
R11	0.01
R12	0.01
R13	0.01
R14	0.01

Table A-25: GHG emissions of exporting intermediate rubber products from freight route to destination: ET_{bd} (Unit: Baht/Ton)

GHG emissions at 100 is assumed for conservation flow

CT_{bd}		d					
		CTS	DOS	SKP	PNG	BKK	LCB
b	R1	0.01	100	100	100	100	100
	R2	100	0.01	100	100	100	100
	R3	100	100	0.01	100	100	100
	R4	100	100	100	0.01	100	100
	R5	100	100	100	0.01	100	100
	R6	100	100	100	0.01	100	100
	R7	100	100	100	0.01	100	100
	R8	100	100	100	100	0.01	100
	R9	100	100	100	100	100	0.01
	R10	100	100	100	100	0.01	100
	R11	100	100	100	100	100	0.01
	R12	100	100	100	100	0.01	100
	R13	100	100	100	100	100	0.01
	R14	100	100	100	100	100	0.01

Table A-26: Chapter 4 result of solving costs minimisation model (objective function 1): (Unit: Ton per month)

X						Y				Z			
Province (i)	Farm size (s)	Primary Rubber (p)	Truck Type (t)	Trading Group (g)	Amount (Ton)	Factory (f)	Intermediate Rubber (e)	G.W Node (a)	Amount (Ton)	Intermediate Rubber (e)	Route (b)	Destination (d)	Amount (Ton)
Trang	S	US	4W	DL	4,805	4	LCT	D1	9,064	STR	R2	DOS	8,848
		CL	4W	DL	0		RSS	D1	3,000		R3	SKP	7,487
		LX	4W	DL	2,141						R4	PNG	12,882
			4W	CO	3,000						R5	PNG	4,443
	M	US	10W	DL	1,513					RSS	R2	DOS	7,033
	L	CL	10W	DL	605						R3	SKP	5,951
Pattalung	S	US	4W	DL	4,523	4	LCT	D1	13,020		R5	PNG	18,057
		CL	4W	DL	2,613					LCT	R2	DOS	4,017
		LX	4W	DL	1,035						R3	SKP	5,759
		LX	4W	CO	3,938						R4	PNG	15,198
	M	US	4W	DL	651								
	L	CL	10W	DL	260								
Satun	S	US	4W	DL	715	4	LCT	D	2,890				
		CL	4W	DL	1,464		RSS	D1	1,313				
		LX	4W	DL	214								
			4W	CO	1,313								
	M	US	4W	DL	355								
	L	CL	10W	DL	142								
Songkhla	S	US	4W	DL	9,961	4	STR	D1	33,660				
		US	4W	GM	1,933								
		CL	4W	DL	9,756								
		LX	4W	DL	3,586								
			4W	GM	1,004								
			4W	CO	5,063								
	M	US	4W	GM	1,683								
	L	CL	10W	DL	673								
Pattani	S	US	4W	DL	1,887	4	RSS	D1	6,209				
		CL	4W	DL	3,208								
		LX	4W	DL	446								
			4W	CO	188								
	M	US	4W	DL	343								
	L	CL	10W	DL	137								
Yala	S	US	4W	DL	5,392	4	RSS	D1	18,667				
		CL	4W	DL	9,418								
		LX	4W	DL	1,320								
			4W	CO	844								
	M	US	4W	DL	1,209								
	L	CL	10W	DL	484								

Narathiwat	S	LX	4W	DL	288	4	RSS	D1	1,852				
	M	LX	10W	DL	836								
			10W	CO	281								
	L	CL	10W	DL	447								
Chumporn	S	LX	4W	DL	1,484	10	STR	D2	1,731	STR	R1	CTS	2,133
			4W	CO	414		RSS	D2	1,031		R7	PNG	6,496
	M	LX	10W	CO	617						R8	BKK	3,706
	L	LX	10W	DL	247						R14	LCB	3,654
Ranong	S	LX	4W	DL	1,195	10	STR	D2	1,288	RSS	R1	CTS	2,404
		LX	4W	CO	48		RSS	D2	282		R7	PNG	878
	M	US	10W	DL	233						R14	LCB	12,443
										LCT	R2	DOS	2,789
Suratthani	S	US	4W	DL	15,076	10	STR	D2	12,970		R7	PNG	3,126
		US	4W	GM	861		RSS	D2	11,851		R14	LCB	12,041
		CL	4W	DL	16,736		LCT	D2	17,956				
		LX	4W	DL	3,015								
			4W	GM	1,000								
			4W	CO	3,094								
	M	US	4W	GM	2,139								
	L	CL	10W	DL	856								
Phangnga	S	LX	4W	DL	642	10	RSS	D2	2,312				
			4W	CO	421								
	M	LX	10W	CO	892								
	L	CL	10W	DL	357								
Nakhon Si	S	US	4W	DL	12,043	12	STR	D3	19,092				
Thammarat		US	4W	GM	1,633		LCT	D3	9,947	STR	R1	CTS	4,673
		CL	4W	DL	6,795		RSS	D3	4,300		R12	BKK	2,419
		LX	4W	DL	2,409						R13	LCB	12,000
			4W	GM	1,000					RSS	R1	CTS	3,006
			4W	CO	7,125						R12	BKK	4,869
	M	US	4W	GM	1,667					LCT	R1	CTS	5,235
	L	CL	10W	DL	667						R12	BKK	4,712
Krabi	S	LX	4W	DL	856	12	RSS	D3	3,575				
			4W	CO	1,735								
	M	LX	10W	CO	703								
	L	CL	10W	DL	281								
Phuket	S	LX	4W	DL	113	12	RSS	D3	250				
	M	LX	10W	CO	94								
	L	LX	10W	DL	39								

Chapter 4 result of solving costs minimisation model (objective function 1):

Table A-27: The percentage of optimal primary rubber production

Primary rubber product	The percentage of optimal primary rubber production
US	39%
CL	31%
LX	30%

Table A-28: The percentage of optimal farmer size production

Farmer size	The percentage of optimal farmer size production
S	90%
M	8%
L	3%

Table A-29: The percentage of optimal intermediate rubber production

Intermediate rubber product	The percentage of optimal intermediate rubber production
STR	39%
RSS	31%
LCT	30%

Table A-30: The percentage of optimal trading rubber volume in each trader group

Trader group	The percentage of optimal trading rubber volume
DL	76%
CO	17%
GM	7%

Table A-31: The percentage of optimal volume delivered in each truck type

Truck type	The percentage of optimal volume delivered in each truck type
4W	96%
10W	4%

Table A-32: Chapter 4 result of solving GHG emissions minimisation model (objective function 2): (Unit: Ton per month)

X						Y				Z			
Province (i)	Farm size (s)	Primary Rubber (p)	Truck Type (t)	Trading Group (g)	Amount (Ton)	Factory (f)	Intermediate Rubber (e)	G.W Node (a)	Amount (Ton)	Intermediate Rubber (e)	Route (b)	Destination (d)	Amount (Ton)
Trang	S	US	10W	DL	8,842	4	LCT	D1	2,965	STR	R3	SKP	7,487
		LX	10W	DL	2,141		RSS	D1	11,018		R4	PNG	9,756
			10W	CO	3,000						R5	PNG	3,565
										RSS	R3	SKP	5,951
											R5	PNG	18,935
Pattalung	S	CL	10W	DL	7,136	4	LCT	D1	13,020	LCT	R3	SKP	5,759
		LX	10W	DL	1,035						R4	PNG	18,324
		LX	10W	CO	3,938								
	M	US	10W	DL	651								
	L	US	10W	DL	260								
Satun	S	US	10W	DL	1,070	4	LCT	D1	1,313				
		CL	10W	DL	1,606		RSS	D1	2,890				
		LX	10W	DL	214								
		LX	10W	CO	1,313								
Songkhla	S	US	10W	DL	15,866	4	STR	D1	20,808				
		CL	10W	DL	6,458		LCT	D1	6,785				
		LX	10W	DL	3,586		RSS	D1	6,067				
			10W	GM	331								
			10W	CO	5,063								
	M	US	10W	DL	1,683								
	L	LX	4W	GM	673								
Pattani	S	US	10W	DL	2,230	4	RSS	D1	6,209				
		CL	10W	DL	3,345								
		LX	10W	DL	446								
			10W	CO	188								
Yala	S	LX	10W	DL	1,320	4	RSS	D1	2,164				
			10W	CO	844								
Narathiwat	S	LX	10W	DL	1,124	4	RSS	D1	1,405				
			10W	CO	281								
Chumporn	S	LX	10W	DL	1,731	10	LCT	D2	1,031	STR	R1	CTS	6,806
			10W	CO	1,031		RSS	D2	1,731		R2	DOS	8,848
											R14	LCB	3,654
Ranong	S	US	10W	DL	2,849	10	LCT	D2	3,676	RSS	R1	CTS	5,410

	  M L	LX LX US US	10W 10W 10W 10W	DL CO DL DL	1,195 281 233 93		RSS	D2	975	 LCT	R2 R14 R1 R2 R14	DOS LCB CTS DOS LCB	7,033 12,443 5,235 6,806 12,041
Suratthani	S M L	US CL LX US LX	10W 10W 10W 10W 10W 10W 4W	DL DL DL GM CO DL GM	12,937 20,592 3,015 144 3,094 2,139 856	10	STR RSS LCT	D2 D2 D2	19,308 4,094 19,375				
Phangnga	S	US CL LX	10W 10W 10W 10W	DL DL DL CO	3,211 4,817 642 1,313	10	RSS	D2	9,983				
Nakhon Si Thammarat	S M L	US CL LX LX LX US LX	10W 10W 10W 10W 10W 10W 4W	DL DL DL GM CO DL GM	10,376 10,891 2,409 204 7,125 1,667 667	12	STR LCT	D3 D3	28,625 4,712	STR RSS LCT	R7 R12 R13 R12 R8 R12	PNG BKK LCB BKK BKK BKK	10,500 6,125 12,000 4,869 3,706 1,006
Krabi	S	US CL LX	10W 10W 10W 10W	DL DL DL CO	4,282 148 856 2,438	12	RSS	D3	7,724				
Phuket	S	LX	10W 10W	DL CO	285 94	12	RSS	D3	379				

Chapter 4 result of solving GHG emissions minimisation model (objective function 2)

Table A-33: The percentage of optimal primary rubber production

Primary rubber product	The percentage of optimal primary rubber production
US	39%
CL	31%
LX	30%

Table A-34: The percentage of optimal farmer size production

Farmer size	The percentage of optimal farmer size production
S	95%
M	4%
L	1%

Table A-35: The percentage of optimal intermediate rubber production

Intermediate rubber product	The percentage of optimal intermediate rubber production
STR	39%
RSS	31%
LCT	30%

Table A-36: The percentage of optimal trading rubber volume in each trader group

Trader group	The percentage of optimal trading rubber volume
DL	81%
CO	17%
GM	2%

Table A-37: The percentage of optimal volume delivered in each truck type

Truck type	The percentage of optimal volume delivered in each truck type
4W	1%
10W	99%

Table A-38: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	199,550	16,045
2	199,390	16,045
3	199,230	16,046
4	199,070	16,046
5	198,910	16,046
6	198,750	16,046
7	198,590	16,046
8	198,430	16,046
9	198,270	16,046
10	198,110	16,046
11	197,950	16,046
12	197,790	16,046
13	197,630	16,046
14	197,470	16,046
15	197,310	16,046
16	197,150	16,046
17	196,990	16,046
18	196,830	16,046
19	196,670	16,046
20	196,510	16,046
21	196,350	16,046
22	196,190	16,047
23	196,030	16,047
24	195,870	16,047
25	195,710	16,047
26	195,550	16,048
27	195,390	16,048
28	195,230	16,049
29	195,070	16,049
30	194,910	16,050
31	194,750	16,050
32	194,590	16,051
33	194,430	16,052
34	194,270	16,053
35	194,110	16,053
36	193,950	16,054
37	193,790	16,055
38	193,630	16,056
39	193,470	16,057
40	193,310	16,058
41	193,150	16,059
42	192,990	16,060
43	192,830	16,062
44	192,670	16,063
45	192,510	16,064
46	192,350	16,066
47	192,190	16,069
48	192,030	16,072
49	191,870	16,076
50	191,710	16,082

Table A-39: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method: Transportation restructure scenarios 1 (Increase rail freight service capacity by 25% of route R5, R6, R7, R10, R11, R12, R13)

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	197,000	16,043
2	196,772	16,043
3	196,544	16,043
4	196,316	16,043
5	196,088	16,043
6	195,860	16,043
7	195,632	16,043
8	195,404	16,043
9	195,176	16,044
10	194,948	16,044
11	194,720	16,044
12	194,492	16,044
13	194,264	16,044
14	194,036	16,044
15	193,808	16,044
16	193,580	16,044
17	193,352	16,044
18	193,124	16,044
19	192,896	16,044
20	192,668	16,044
21	192,440	16,045
22	192,212	16,045
23	191,984	16,046
24	191,756	16,047
25	191,528	16,047
26	191,300	16,049
27	191,072	16,050
28	190,844	16,051
29	190,616	16,052
30	190,388	16,053
31	190,160	16,054
32	189,932	16,056
33	189,704	16,058
34	189,476	16,060
35	189,248	16,062
36	189,020	16,064
37	188,792	16,071
38	188,564	16,071
39	188,336	16,077
40	188,108	16,085
41	187,880	16,095
42	187,652	16,104
43	187,424	16,114
44	187,196	16,124
45	186,968	16,133
46	186,740	16,143
47	186,512	16,152
48	186,284	16,162
49	186,056	16,172
50	185,828	16,183

Table A-40: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method: Transportation restructure scenarios 2 (Increase rail freight service capacity by 50% of route R5, R6, R7, R10, R11, R12, R13)

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	195,200	16,041
2	194,974	16,041
3	194,748	16,041
4	194,522	16,041
5	194,296	16,041
6	194,070	16,042
7	193,844	16,042
8	193,618	16,042
9	193,392	16,042
10	193,166	16,042
11	192,940	16,042
12	192,714	16,042
13	192,488	16,042
14	192,262	16,042
15	192,036	16,042
16	191,810	16,042
17	191,584	16,042
18	191,358	16,043
19	191,132	16,043
20	190,906	16,043
21	190,680	16,043
22	190,454	16,043
23	190,228	16,044
24	190,002	16,044
25	189,776	16,045
26	189,550	16,046
27	189,324	16,047
28	189,098	16,048
29	188,872	16,050
30	188,646	16,051
31	188,420	16,052
32	188,194	16,054
33	187,968	16,056
34	187,742	16,058
35	187,516	16,060
36	187,290	16,064
37	187,064	16,070
38	186,838	16,079
39	186,612	16,089
40	186,386	16,098
41	186,160	16,108
42	185,934	16,117
43	185,708	16,127
44	185,482	16,136
45	185,256	16,146
46	185,030	16,155
47	184,804	16,166
48	184,578	16,177
49	184,352	16,189
50	184,126	16,201

Table A-41: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method: Transportation restructure scenarios 3 (Increase rail freight service capacity by 75% of route R5, R6, R7, R10, R11, R12, R13)

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	193,800	16,040
2	193,574	16,040
3	193,348	16,040
4	193,122	16,040
5	192,896	16,040
6	192,670	16,040
7	192,444	16,040
8	192,218	16,040
9	191,992	16,040
10	191,766	16,040
11	191,540	16,040
12	191,314	16,040
13	191,088	16,041
14	190,862	16,041
15	190,636	16,041
16	190,410	16,041
17	190,184	16,041
18	189,958	16,041
19	189,732	16,041
20	189,506	16,041
21	189,280	16,041
22	189,054	16,042
23	188,828	16,042
24	188,602	16,043
25	188,376	16,044
26	188,150	16,045
27	187,924	16,046
28	187,698	16,047
29	187,472	16,048
30	187,246	16,049
31	187,020	16,051
32	186,794	16,053
33	186,568	16,055
34	186,342	16,057
35	186,116	16,060
36	185,890	16,068
37	185,664	16,078
38	185,438	16,087
39	185,212	16,096
40	184,986	16,106
41	184,760	16,115
42	184,534	16,125
43	184,308	16,134
44	184,082	16,144
45	183,856	16,153
46	183,630	16,163
47	183,404	16,175
48	183,178	16,186
49	182,952	16,199
50	182,726	16,214

Table A-42: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method: Transportation restructure scenarios 4 (Increase rail freight service capacity by 100% of route R5, R6, R7, R10, R11, R12, R13)

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	193,100	16,038
2	192,858	16,038
3	192,616	16,038
4	192,374	16,038
5	192,132	16,038
6	191,890	16,038
7	191,648	16,039
8	191,406	16,039
9	191,164	16,039
10	190,922	16,039
11	190,680	16,039
12	190,438	16,039
13	190,196	16,039
14	189,954	16,039
15	189,712	16,039
16	189,470	16,039
17	189,228	16,039
18	188,986	16,039
19	188,744	16,040
20	188,502	16,040
21	188,260	16,040
22	188,018	16,040
23	187,776	16,041
24	187,534	16,041
25	187,292	16,042
26	187,050	16,043
27	186,808	16,044
28	186,566	16,045
29	186,324	16,046
30	186,082	16,047
31	185,840	16,048
32	185,598	16,050
33	185,356	16,052
34	185,114	16,054
35	184,872	16,061
36	184,630	16,071
37	184,388	16,081
38	184,146	16,091
39	183,904	16,101
40	183,662	16,111
41	183,420	16,122
42	183,178	16,132
43	182,936	16,142
44	182,694	16,152
45	182,452	16,164
46	182,210	16,177
47	181,968	16,192
48	181,726	16,212
49	181,484	16,235
50	181,242	16,260

Table A-43: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method: Four distribution node (Trang, Songkhla,Nakhon Si Thammarat, Suratthani)

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	197,500	15,889
2	197,500	15,889
3	197,390	15,889
4	197,280	15,889
5	197,170	15,889
6	197,060	15,889
7	196,950	15,889
8	196,840	15,889
9	196,730	15,889
10	196,620	15,889
11	196,510	15,889
12	196,400	15,889
13	196,290	15,889
14	196,180	15,889
15	196,070	15,889
16	195,960	15,889
17	195,850	15,889
18	195,740	15,889
19	195,630	15,889
20	195,520	15,889
21	195,410	15,889
22	195,300	15,889
23	195,190	15,889
24	195,080	15,890
25	194,970	15,890
26	194,860	15,890
27	194,750	15,890
28	194,640	15,891
29	194,530	15,892
30	194,420	15,892
31	194,310	15,893
32	194,200	15,894
33	194,090	15,894
34	193,980	15,895
35	193,870	15,896
36	193,760	15,897
37	193,650	15,898
38	193,540	15,899
39	193,430	15,900
40	193,320	15,901
41	193,210	15,902
42	193,100	15,903
43	192,990	15,905
44	192,880	15,906
45	192,770	15,908
46	192,660	15,910
47	192,550	15,912
48	192,440	15,914
49	192,330	15,916
50	192,100	15,920

Table A-44: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method: Five distribution node (Trang, Songkhla,Nakhon Si Thammarat, Suratthani, Chumporn)

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	198,000	15,889
2	197,808	15,889
3	197,616	15,889
4	197,424	15,889
5	197,232	15,889
6	197,040	15,889
7	196,848	15,889
8	196,656	15,889
9	196,464	15,889
10	196,272	15,889
11	196,080	15,889
12	195,888	15,889
13	195,696	15,889
14	195,504	15,889
15	195,312	15,889
16	195,120	15,889
17	194,928	15,890
18	194,736	15,890
19	194,544	15,891
20	194,352	15,892
21	194,160	15,893
22	193,968	15,894
23	193,776	15,896
24	193,584	15,896
25	193,392	15,896
26	193,200	15,896
27	193,008	15,903
28	192,816	15,906
29	192,624	15,908
30	192,432	15,912
31	192,240	15,916
32	192,048	15,921
33	191,856	15,928
34	191,664	15,936
35	191,472	15,945
36	191,280	15,958
37	191,088	15,971
38	190,896	15,984
39	190,704	15,997
40	190,512	16,011
41	190,320	16,025
42	190,128	16,039
43	189,936	16,067
44	189,744	16,096
45	189,552	16,126
46	189,360	16,155
47	189,168	16,185
48	188,976	16,223
49	188,784	16,284
50	188,400	16,406

Table A-45: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method: Four distribution node (Trang, Songkhla,Nakhon Si Thammarat, Suratthani) with new transportation route R15

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	210,000	15,876
2	209,620	15,876
3	209,240	15,876
4	208,860	15,876
5	208,480	15,876
6	208,100	15,876
7	207,720	15,876
8	207,340	15,876
9	206,960	15,876
10	206,580	15,876
11	206,200	15,876
12	205,820	15,876
13	205,440	15,876
14	205,060	15,876
15	204,680	15,876
16	204,300	15,876
17	203,920	15,877
18	203,540	15,877
19	203,160	15,877
20	202,780	15,878
21	202,400	15,878
22	202,020	15,879
23	201,640	15,880
24	201,260	15,880
25	200,880	15,881
26	200,500	15,881
27	200,120	15,882
28	199,740	15,882
29	199,360	15,883
30	198,980	15,884
31	198,600	15,884
32	198,220	15,885
33	197,840	15,885
34	197,460	15,886
35	197,080	15,886
36	196,700	15,887
37	196,320	15,887
38	195,940	15,888
39	195,560	15,889
40	195,180	15,889
41	194,800	15,890
42	194,420	15,892
43	194,040	15,894
44	193,660	15,897
45	193,280	15,900
46	192,900	15,904
47	192,520	15,910
48	192,140	15,919
49	191,760	15,932
50	191,000	15,977

Table A-46: The Pareto set of solutions for minimising costs and GHG emissions using the ε -Constraint Method: Five distribution node (Trang, Songkhla,Nakhon Si Thammarat, Suratthani, Chumporn) with new transportation route R15

Sub-interval	ε parameter value (GHG emissions; Ton)	Costs (Million Baht)
1	208,200	15,876
2	207,608	15,876
3	207,216	15,876
4	206,824	15,876
5	206,432	15,876
6	206,040	15,876
7	205,648	15,876
8	205,256	15,876
9	204,864	15,876
10	204,472	15,876
11	204,080	15,876
12	203,688	15,877
13	203,296	15,877
14	202,904	15,878
15	202,512	15,878
16	202,120	15,879
17	201,728	15,879
18	201,336	15,880
19	200,944	15,881
20	200,552	15,881
21	200,160	15,882
22	199,768	15,882
23	199,376	15,883
24	198,984	15,884
25	198,592	15,884
26	198,200	15,885
27	197,808	15,885
28	197,416	15,886
29	197,024	15,886
30	196,632	15,887
31	196,240	15,888
32	195,848	15,888
33	195,456	15,889
34	195,064	15,889
35	194,672	15,891
36	194,280	15,893
37	193,888	15,895
38	193,496	15,898
39	193,104	15,902
40	192,712	15,907
41	192,320	15,914
42	191,928	15,926
43	191,536	15,941
44	191,144	15,967
45	190,752	15,994
46	190,360	16,022
47	189,968	16,062
48	189,576	16,122
49	189,184	16,182
50	188,400	16,406

Table A-47: Sensitivity Analysis scenarios value (The values are random from normal distribution (mean = 0))

Scenario	Production value (Ton)	Demand value (Ton)
1	263,608	180,554
2	267,809	177,533
3	272,048	176,733
4	255,721	168,272
5	270,269	175,752
6	263,395	170,862
7	273,639	182,776
8	278,719	183,870
9	259,557	177,222
10	265,044	177,879

Table A-48: Percentage of deviation in terms of changes in objective function values when production changes

Scenario	Production value (Ton)	Objective function value (Total costs: Baht)	% of deviation from Baseline	Objective function value (Total GHG emissions: Ton)	% of deviation from Baseline
Baseline	264,412	16,045,402,681		60,683.337	
1	263,608	16,069,357,314	0.1490%	60,959.293	0.0095%
2	267,809	16,045,267,380	-0.0008%	59,913.099	0.0033%
3	272,048	16,029,637,535	-0.0010%	58,922.092	-0.0045%
4	255,721	16,081,061,607	0.0022%	62,885.181	0.0208%
5	270,269	16,028,770,845	-0.0010%	59,306.730	0.0007%
6	263,395	16,073,690,660	0.0018%	61,025.040	0.0250%
7	273,639	16,028,553,275	-0.0011%	58,575.543	0.0043%
8	278,719	16,029,641,577	-0.0010%	57,511.836	-0.0056%
9	259,557	16,039,993,738	-0.0003%	61,797.577	0.0049%
10	265,044	16,035,590,060	-0.0006%	60,501.615	0.0043%

Table A-49: Percentage of deviation in terms of changes in objective function values when demand changes

Scenario	Demand value (Ton)	Objective function value (Total costs: Baht)	% of deviation from Baseline	Objective function value (Total GHG emissions: Ton)	% of deviation from Baseline
Baseline	176,259	15,919,340,615		90,317.888	
1	180,554	16,294,158,076	2.3545%	90,245.345	3.0372%
2	177,533	16,025,984,423	0.6699%	90,270.453	1.0079%
3	176,733	15,923,355,804	0.0252%	90,098.373	0.5118%
4	168,272	15,182,690,502	-4.6274%	90,227.075	-4.5344%
5	175,752	15,882,176,412	-0.2335%	90,366.974	-0.5965%
6	170,862	15,414,900,640	-3.1687%	90,218.425	-3.8893%
7	182,776	16,565,149,762	4.0568%	90,630.880	4.4821%
8	183,870	16,625,174,349	4.4338%	90,418.090	3.7466%
9	177,222	15,981,267,496	0.3890%	90,176.544	-0.4323%
10	177,879	16,082,330,596	1.0238%	90,411.631	1.7810%